University of Alberta

# RELIABILITY ANALYSIS OF CONCENTRICALLY LOADED FILLET WELDS

by

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## ABSTRACT

Tests on joints of cruciform configuration conducted in a previous test program indicated that fillet welds in these joints may possess reduced strength and ductility compared to transverse welds in lapped joints. An experimental program consisting of 12 fillet weld cruciform specimens was conducted to investigate effect of root notch orientation on weld strength and ductility. The reliability analyses presented in the previous phases of this program were conducted using mostly test results obtained at the University of Alberta. To augment this database of test results, test data from various test programs on lapped splices with single and multiple orientation welds and on cruciform test specimens were collected. This provides a larger database of test results, which better reflect the variation present in industry. A reliability analysis was conducted to assess the current North American and proposed design equations for lapped joints with single and multiple orientation welds and for cruciform connections.

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## TABLE OF CONTENTS


1. INTRODUCTION ..... 1

1.1 Background ..... 1

1.2 Objectives and Scope ..... 2

1.3 Units Used in this Report ..... 3

2. LITERATURE REVIEW ..... 4

2.1 Introduction ..... 4

2.2 Fillet Weld Strength as a Function of Loading Direction ..... 4

2.3 Strength of Cruciform Fillet Weld Specimens ..... 8

2.4 Load Capacity of Joints with Multiple Orientation Fillet Welds (MOFW) ..... 10

2.5 Effects of Weld Sizes and Lengths on Fillet Weld Strength ..... 10

2.6 Summary ..... 12

3. EXPERIMENTAL PROGRAM AND RESULTS ..... 14

3.1 Introduction ..... 14

3.2 Test Parameters ..... 14

3.3 Specimens Description ..... 16

3.4 Pre-Test Measurements ..... 16

3.5 Instrumentation and Test Procedure ..... 17

3.6 Main Plates Misalignment Second Order Effects ..... 18

3.7 Cruciform Specimen Capacities ..... 19

3.8 Weld Strains Calculated from Deformations Measured with LVDTs ..... 20

3.9 Effect of Root Notch Orientation on Weld Strength ..... 21

3.10 Effect of Root Notch Orientation on Ductility ..... 22

4. ANALYSIS OF TEST RESULTS ..... 45

4.1 Introduction ..... 45

4.2 Summary of Test Data from Different Sources ..... 50

4.2.1 Geometric Factor, $\rho_G$ ..... 50
4.2.2 Material Factor, $p_{M1}$ ..... 51
4.2.3 Material Factor, $\rho_{M2}$ ..... 52
4.2.4 Professional Factor, $\rho_P$ , for Joints with Only One Weld Orientation ..... 53
4.2.5 Professional Factor, $\rho_P$ , for Joints with Multiple Weld Orientations ..... 53
4.2.6 Professional Factor, $\rho_P$ , for Cruciform Connections ..... 54
4.3 Safety Level of Lapped Splice Connections ..... 54
4.3.1 Connections with Single Orientation Fillet Welds ..... 54
4.3.2 Connections with Fillet Welds Oriented in Multiple Directions ..... 55
4.4 Safety Level of Cruciform Connections ..... 56

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS ..... 81
5.1 Summary ..... 81
5.2 Conclusions ..... 82
5.3 Recommendations for Future Research ..... 85

REFERENCES ..... 87

APPENDIX A – ALL-WELD-METAL TENSION COUPON TESTS ..... 91
APPENDIX B – FILLET WELD SPECIMEN MEASUREMENTS ..... 96
APPENDIX C – SPECIMEN RESPONSE CURVES (ROOM TEMPERATURE TESTS) ..... 104
APPENDIX D – RESULTS OF WELD TESTS AT LOW TEMPERATURE ..... 120
APPENDIX E – RESULTS OF OTHER TEST PROGRAMS ..... 129
APPENDIX F – NEW SPECIMEN DESIGN DRAWINGS ..... 251
APPENDIX G – RESULT OF ADDITIONAL SIX SPECIMENS TESTED IN PHASE 4 ..... 265

## LIST OF TABLES


| | | |
|---|---|---|
| Table 3.1 | Test Matrix – Cruciform Specimens | 24 |
| Table 3.2 | Mechanical Properties of Weld Metal | 24 |
| Table 3.3 | Summary of Pre-Test Weld Measurements | 25 |
| Table 3.4 | Measured Eccentricities in the Cruciform Specimens | 26 |
| Table 3.5 | Bending Effect on Cruciform Specimens | 27 |
| Table 3.6 | Summary of Test Capacities Obtained at Room Temperature | 28 |
| Table 3.7 | Ultimate and Fracture Weld Deformations and Strains | 28 |
| Table 3.8a | Comparison of Fillet Weld Strength (12.7 mm, E70T–7) | 29 |
| Table 3.8b | Comparison of Fillet Weld Strength (12.7 mm, E71T8–K6) | 30 |
| Table 3.8c | Comparison of Fillet Weld Strength (6.4 mm, E70T–4) | 31 |
| Table 3.8d | Comparison of Fillet Weld Strength (6.4 mm, E70T7–K2) | 32 |
| Table 3.9 | Summary of Strength Ratio | 33 |
| Table 3.10a | Comparison of Fillet Weld Strains (12.7 mm, E70T–7) | 34 |
| Table 3.10b | Comparison of Fillet Weld Strains (12.7 mm, E71T8–K6) | 35 |
| Table 3.10c | Comparison of Fillet Weld Strains (6.4 mm, E70T–4) | 36 |
| Table 3.10d | Comparison of Fillet Weld Strains (6.4 mm, E70T7–K2) | 37 |
| Table 4.1 | Summary of Geometric Factor $\rho_G$ from Various Sources | 57 |
| Table 4.2 | Geometric Factor $\rho_G$ for Specimens from Current Test Program | 59 |
| Table 4.3 | Summary of Geometric Factor $\rho_G$ from Phase 1 through 4 | 60 |
| Table 4.4 | Summary of Material Factor $\rho_{M1}$ | 61 |
| Table 4.5 | Summary of Material Factor $\rho_{M2}$ per Equation 4.6a | 62 |
| Table 4.6 | Summary of Professional Factor $\rho_P$ for SOFW Joints | 63 |
| Table 4.7a | Summary of Professional Factor $\rho_P$ for MOFW Joints for Equation 4.9 | 65 |
| Table 4.7b | Summary of Professional Factor $\rho_P$ for MOFW Joints for Equation 4.10 | 66 |

Table 4.7c Summary of Professional Factor $\rho_P$ for MOFW Joints for Equation 4.11a and b ..... 67
Table 4.8 Professional Factor $\rho_P$ for Cruciform Specimens from Phase 1 and 4 ..... 68
Table 4.9 Summary of Professional Factor $\rho_P$ for Cruciform Connections ..... 69
Table 4.10 Summary of Safety Indices for SOFW Joints ..... 70
Table 4.11 Summary of Safety Indices for MOFW Joints ..... 71
Table 4.12 Summary of Safety Indices for SOFW Specimens with Out-of-plane Eccentricity from Ligtenberg (1968) ..... 72
Table 4.13 Summary of Safety Indices for Cruciform Joints ..... 73

## LIST OF FIGURES


| | | |
|---|---|---|
| Figure 3.1 | Dimensions of Cruciform Test Specimens | 38 |
| Figure 3.2 | Definition of Fillet Weld Pre-Test Measurements | 39 |
| Figure 3.3 | Eccentricity Measurements | 40 |
| Figure 3.4 | Weld Deformation Measurements | 41 |
| Figure 3.5 | Arrangement of Strain Gauges | 42 |
| Figure 3.6 | Load Eccentricity and Bending Effect | 43 |
| Figure 3.7 | Effect of Root Notch Orientation on Weld Strength | 43 |
| Figure 4.1 | Variation of $\rho_G$ and $V_G$ with Weld Size | 74 |
| Figure 4.2 | Value of $\rho_{M1}$ as a Function of the Nominal Tensile Strength from Various Sources | 75 |
| Figure 4.3 | Variation of $\rho_{M1}$ in Various Data Sets | 75 |
| Figure 4.4 | Werner Specimen | 76 |
| Figure 4.5 | Bias Coefficient $\rho_{M2}$ as a Function of Weld Size | 76 |
| Figure 4.6 | Effect of Tensile Strength on the Bias Coefficient $\rho_{M2}$ for All Test Specimens in Table 4.5 | 77 |
| Figure 4.7 | Professional Factor $\rho_P$ for Transverse Weld versus Measured Weld Size | 77 |
| Figure 4.8 | Professional Factor $\rho_P$ for Transverse Weld versus Measured Filler Metal Tensile Strength | 78 |
| Figure 4.9 | MOFW Specimen with Out-of-plane Eccentricity from Ligtenberg (1968) | 79 |
| Figure 4.10 | Professional Factor $\rho_P$ for Combined Transverse and Longitudinal Welds versus Measured Filler Metal Tensile Strength | 80 |

## LIST OF SYMBOLS†

| | |
|---|---|
| $A_{throat}$ | Measured throat area of the weld ($mm^2$) |
| $A_w$ | Theoretical throat area of the weld ($mm^2$) |
| $C$ | Adjustment factor for the weld resistance factor |
| *CPL* | The central plate leg is the fillet weld leg that is on the central plate of the cruciform specimen (mm) |
| $CRF(\theta)$ | Combination reduction factor for any fillet weld orientation, θ. |
| $d^*$ | Average measured fillet weld leg dimension (mm) |
| *LPL* | The lap plate leg is the fillet weld leg that is on the lap plate of the lapped specimen (mm) |
| *MOFW* | Multi-orientation fillet weld |
| *MPL* | The main plate leg is the fillet weld leg that is on the main plate of the specimen (mm) |
| *MTD* | Measured throat dimension (mm), see definition in Section 4.1 |
| *Normalized* $P_{ST}/A_{throat}$ | The value of the term ( $P/A_{throat}$ ) divided by the ultimate tensile strength of the filler metal |
| $P$ | Applied load (kN) |
| $P_{ST}$ | Maximum applied static load (kN) |
| $P_u$ | Maximum applied load (kN) |
| $P_u$ | Capacity of a weld with a loading angle of $\theta$ (kN) |
| $s_1$, $s_2$ | Fillet weld leg dimensions (mm) |
| *SOFW* | Single orientation fillet weld |
| $V_G$ | Coefficient of variation for the measured-to-nominal weld dimension |

| | |
|---|---|
| $V_{M1}$ | Coefficient of variation for the measured-to-nominal ultimate tensile strength of the filler metal |
| $V_{M2}$ | Coefficient of variation for the measured-to-predicted ultimate shear strength of the filler metal |
| $V_P$ | Coefficient of variation for the test-to-predicted weld capacity |
| $V_R$ | Coefficient of variation for the resistance of the weld |
| $V_r$ | Capacity of a fillet weld connection |
| $X_u$ | Nominal ultimate tensile strength of the filler metal (MPa) |
| $\alpha_R$ | Coefficient of separation |
| $\beta$ | Reliability index |
| $\Delta$ | Fillet weld deformation (mm) |
| $\Delta_f$ | Fillet weld deformation at weld fracture (mm) |
| $\Delta_{ult}$ | Fillet weld deformation at ultimate load (mm) |
| $\varepsilon$ | Strain measured by strain gauge |
| $\varepsilon_y$ | Strain equal to $1750\times10^{-6}$ |
| $\theta$ | Angle between the axis of the fillet weld and the direction of the applied load (degrees) |
| $\lambda$ | Regression coefficient used to characterize fillet weld response |
| $\mu$ | Regression coefficient used to characterize fillet weld response |
| $\rho_G$ | Bias coefficient for the theoretical weld dimension |
| $\rho_{M1}$ | Bias coefficient for the ultimate tensile strength of the filler metal |
| $\rho_{M2}$ | Bias coefficient for the ultimate shear strength of the filler metal |

| | |
|---|---|
| $\rho_P$ | Mean test-to-predicted weld capacity |
| $\rho_R$ | Bias coefficient for the resistance of the weld |
| $\sigma_u$ | The tensile strength of the weld metal |
| $\tau_u$ | Measured ultimate shear strength for a longitudinal weld (MPa) |
| $\phi$ | Resistance factor |
| $\phi_w$ | Weld resistance factor |

† Symbols used in Appendix E may be different from this list and were explained where they appeared in Appendix E.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The effect of load orientation on the strength and ductility of fillet welds has been recognized for a long time (Butler and Kulak, 1971; Clark, 1971 and Miazga and Kennedy, 1989). Transverse fillet welds, loaded at a right angle to the axis of the weld, provide the most strength but least ductility, whereas longitudinal welds provide the least strength, but most ductility. Relationships between load orientation and strength and ductility have been adopted in North American design standards (CSA, 2001; AISC, 2005).

The current design equation for strength of fillet welds used in the North American design standards originated from the work of Miazga and Kennedy (1986, 1989) and Lesik and Kennedy (1990). The test specimens by Miazga and Kennedy were prepared using the shielded metal arc welding (SMAW) process and an E4814 filler metal, which has no toughness requirement. This work was recently expanded by Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al.* (2005) to include the more prevalent flux-cored arc welding (FCAW) process and filler metals both with and without a toughness requirement. The results demonstrated that the current design equation, which acknowledges a strength for transverse welds 50% higher than that for longitudinal welds, provides an adequate level of safety for connections with fillet welds loaded in the plane of the joint.

In the case of a connection that combines welds with different orientations, the ductility of each weld segment must be accounted for when the strength of the joint is evaluated. In a typical welded joint that combines weld segments of different orientations, the weld segments with the least ductility usually develop their full strength, whereas the segments with the most ductility develop only part of their strength. Kulak and Grondin (2003) observed that the only 85% of the strength of longitudinal welds is developed when combined with transverse welds in the same joint. This observation was made from tests

on joints that combined transverse welds, longitudinal welds, and bolts in the same shear plane. Callele *et al.* (2005) further expanded the research work of Ng *et al.* (2002) and Deng *et al.* (2003) to include connections with multiple orientation fillet welds (MOFW). It was demonstrated that the strength of differently oriented weld segments is not fully mobilized at failure of the welded joint. They confirmed the observation of Kulak and Grondin (2003) that when longitudinal welds are combined with a transverse weld in the same joint, only 85% of the strength of the longitudinal weld is mobilized at failure of the joint. Based on their test results, Callele *et al.* (2005) proposed a reliability based procedure to account for the effect of any weld orientation on ductility and contribution to the strength of MOFW.

The weld research program at the University of Alberta has included six different electrode classifications, which represents only a small portion of the electrode classifications used in industry. It is therefore desirable to conduct an extensive review of the literature to augment the database of test results on welded concentrically loaded joints.

### 1.2 Objectives and Scope

This report presents results of the fourth phase of a research project initiated at the University of Alberta to investigate the behaviour of concentrically loaded fillet welded connections. Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005) presented the results of previous three phases of the project.

The fourth phase presents additional test results from welded cruciform joints. Tests on joints of this configuration conducted in phase 1 indicated that fillet welds in these joints may possess reduced strength and ductility compared to transverse welds in lapped joints.

In order to meet the objective of this project, an experimental program consisting of 12 fillet weld cruciform specimens was conducted. All specimens were prepared using the FCAW process and two electrodes, namely, E70T-7 and E71T8-K6. The E70T-7 filler metal has no toughness requirement, while the E71T8-K6 filler metal has a toughness requirement of 20 J at -29°C (AWS 1998).

The reliability analyses presented in the previous phases of this program were conducted using test results obtained primarily at the University of Alberta. Another main objective of this phase is to augment this database of test results to include test results from other sources. This provides a larger database of test results that better reflects the variation present in industry. Test data from various test programs on lapped splices with single and multiple orientation welds and on cruciform test specimens were collected. A reliability analysis was conducted to assess the current North American design equations.

### 1.3 Units Used in this Paper

SI units are generally used throughout this document, although there are exceptions. The filler metal designations use imperial units as implemented in the AWS classification. This exception was made because the AWS classification is more commonly used in industry. The weld sizes are the direct conversion from their imperial units because of the practice adopted by the fabrication workshop.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Although both analytical and experimental investigations of the strength and ductility of fillet welds exist, this review covers only experimental research. The literature review focuses particularly on experimental work conducted from the 1960s to the present on concentrically loaded fillet weld connections, as this is the most relevant to the current research. A detailed literature review of fillet weld research is available from Ng *et al.* (2002).

The test data of some experimental programs are reproduced and analyzed in Appendix E, and the results of those tests are used in Chapter 4 for a reliability analysis.

## 2.2 Fillet Weld Strength as a Function of Loading Direction

Ligtenberg (1968) presented the results of an international test series on double lapped splice fillet weld joints loaded in tension. Including Canada, 11 countries participated in this study and each country performed separate tests under the direction of a common committee. The specimen configurations included longitudinal welds only, transverse welds only, and combined longitudinal and transverse welds with different proportions of weld throat size and weld length. The majority of the test series were performed on St.37 steel (minimum ultimate tensile strength 360 MPa), or material of similar quality, and a few additional test series were carried out on St.52 steel (minimum ultimate tensile strength 510 MPa) to broaden the scope of application of the test results. To diversify the electrodes and welding processes, each country selected three electrodes (acid coated, basic and rutile) in such a way that they were made and commonly used in the participating country. The weld metal tensile strength ranged from about 450 MPa to 580 MPa and the weld throat size ranged from 3 mm to 10 mm. The strength of transverse welds was found to be 1.6 times that of longitudinal fillet welds when the weld strength was defined as one half of the sum of steel plate ultimate tensile strength and the filler metal ultimate tensile strength.

Based on the test results presented by Ligtenberg (1968), Bornscheuer and Feder (1966) designed a test program to investigate further the effect on fillet weld strength of weld length, weld throat dimension, and the ratio of the area of the plate to the cross-sectional area of the fillet weld. The specimen configurations were the same as those reported by Ligtenberg (1968) and a rutile-type electrode was used. The throat dimensions of specimens were 4 mm, 8 mm and 12 mm. The ratio of the strength of transverse welds to that of longitudinal welds was found to be similar to the results presented by Ligtenberg (1968).

After the international test series presented by Ligtenberg (1968), Kato and Morita (1969) reported tests that were designed to further investigate the effects of weld metal mechanical properties, the amount of weld penetration, and weld leg sizes on fillet weld strength. Basic and rutile electrodes were used. The weld leg size ranged from 5 mm to 40 mm for transverse welds and from 5 mm to 22 mm for longitudinal welds. Kato and Morita proposed that the strength of transverse fillet welds was statistically 1.46 times that of longitudinal fillet welds. The test results reported by Ligtenberg (1968) were also used to substantiate their strength prediction formulae.

Higgins and Preece (1969) reported a series of 168 tests on double lapped splice specimens with all longitudinal or all transverse fillet welds. A variety of shielded metal arc welding electrodes (E60XX, E70XX, E90XX and E110XX), base metals (ASTM A36, A441 and A514), fillet weld sizes (6.35 mm, 9.53 mm and 12.7 mm), and weld lengths (from 38.1 mm to 101.6 mm) were used. Another important factor considered in the design of the test specimens was the matching of base metal and the weld metal. For fillet welds made with E70XX electrodes and deposited on matching base metals of grade A441 steel, the strength of transverse welds was found to be 1.57 times that of longitudinal welds. For fillet welds made with E110X electrodes and deposited on matching base metals of grade A514 steel, the average strength of transverse welds was 1.44 times that of longitudinal welds.

Clark (1971) reported a series of 18 tests conducted to investigate the variation of strength and ductility with the loading direction. The specimens included 0°

(longitudinal), 30°, 60° and 90° (transverse) fillet weld orientations. The results showed an increase in strength of approximately 70% as the loading angle changed from 0° to 90°.

Butler and Kulak (1969, 1971) reported a series of 23 concentrically loaded double lapped connections with 6.35 mm (¼ in.) fillet welds of different angles, namely 0° (longitudinal), 30°, 60° and 90° (transverse). The objective of the tests was to establish load–deformation relations for elemental lengths of fillet weld. The results showed that both weld strength and deformation capacity vary with the loading direction. The specimens were prepared using E60XX electrodes and CSA G40.12 steel plates, which have a specified yield strength of 300 MPa and a minimum tensile strength of 450 MPa. The test results showed that the increase in strength of the fillet welds was approximately 44% as the angle of loading changed from 0° to 90°.

Swannell and Skews (1979a, b) reported the results of a series of tests designed to obtain load–deformation relationships for different loading angles. The main specimens were loaded in compression, which differs from most of other test programs. The major tests consisted of six specimens loaded in compression for every loading angle of 0° (longitudinal), 30°, 60° and 90° (transverse). The specimens were prepared using E6013 electrodes and steel plates with a minimum yield strength of 210 MPa and a minimum tensile strength of 410 MPa. The leg size was 6.35 mm. The test results showed an increase in strength of approximately 19% as the angle of loading changed from 0° to 90°.

Miazga and Kennedy (1986, 1989) reported the results of tests on 42 fillet weld double lapped splice specimens loaded in tension. The loading angle varied from 0° to 90° in 15° intervals. Two weld sizes were tested, namely, 5 mm and 9 mm, deposited using the SMAW process with E7014 electrodes. The ratio of the transverse weld strength to the longitudinal weld strength was 1.28 for the 5 mm welds and 1.6 for the 9 mm welds, with an average of 1.43 for all specimens. Based on the measured strength data and the analysis of a free body diagram of a fractured weld, they developed an expression that related weld strength to the loading angle. Later, Lesik and Kennedy (1990) formulated a simplified version of the strength expression proposed by Miazga and Kennedy (1989). The expression of Lesik and Kennedy (1990) takes the following form:

$$P_\theta = P_0 (1.00 + 0.50 \sin^{1.5}\theta) \quad (2.1)$$

where $P_\theta$ is the load capacity of the fillet weld subjected to any direction of loading, $P_0$ is the load capacity of a longitudinal fillet weld of same size, and $\theta$ is the angle between the line of action of the load and the axis of the fillet weld. Equation 2.1 is commonly used in North American design standards to account for the effect of the angle of loading on fillet weld capacity.

Bowman and Quinn (1994) conducted an experimental investigation of geometrical factors that influence the behaviour of fillet welds. The experimental program had 18 specimens, including longitudinal and transverse weld specimens with three leg sizes, namely, 6.35 mm (1/4 in.), 9.53 mm (3/8 in.), and 12.7 mm (1/2 in.), and three different root gap configurations. The welds were prepared using E7018 electrodes. The ratio of the strength of transverse welds to that of longitudinal welds ranged from 1.3 to 1.7 for the un-gapped specimens and 1.2 to 1.4 for the gapped specimens.

Ng *et al.* (2002) conducted tests on 102 transverse fillet weld connection specimens prepared primarily using the flux core arc welding (FCAW) process, although nine specimens were prepared using the shielded metal arc welding (SMAW) process to provide a direct comparison with the test results from Miazga and Kennedy (1989). Of 102 specimens, 96 were double lapped joints and six were cruciform connections. All specimens were concentrically loaded in tension and deformations were measured across the weld leg using LVDTs. The tests were designed to investigate the effect of the following parameters: (1) filler metal classification, both with and without a toughness requirement; (2) welding process, flux cored vs. shielded metal arc melding; (3) weld size and number of passes; (4) welding electrode manufacturers; (5) steel fabricators; (6) low temperature; and (7) root notch orientation of fillet weld, i.e. lapped vs. cruciform splice. The capacity was predicted using Equation (2.1), since it has been adopted by both CSA-S16-01 (CSA 2001) and the AISC Specification (AISC 2005), and the measured weld material strength and fillet weld size. The ratio of tested to predicted strength ranged from 1.14 to 2.30. A reliability analysis was performed for different groups of connections and the safety index, $\beta$, was found to be at least equal to 4.5, which is the traditional target value for connections in the Canadian design standard.

Deng *et al.* (2003) presented the results of 18 tests on joints with longitudinal and 45° fillet welds that were tested to complement the test program reported by Ng et al. (2002). The test specimens were prepared with 12.7 mm fillet welds and three different FCAW electrode classifications. It was reported that the strength of fillet welds increased with increasing loading angle. It was found that the design equation currently used in North America provides an adequate level of safety for joints with single orientation fillet welds.

### 2.3 Strength of Cruciform Fillet Weld Specimens

Pham (1983a) reported results of 36 tests on cruciform specimens, of which 18 were made with the FCAW process and 18 were made with the SAW process. The nominal leg sizes were 6 mm, 10 mm and 16 mm. The primary objectives of the tests were to assess the effect of leg size on the strength of fillet welds and to obtain a corresponding load–deformation relationship. Pham (1983a) did not provide results of transverse welds in lapped joints. The results of his test program, presented in Table E9.5 of Appendix E, show that the ratio of measured strength to predicted strength using Equation (2.1) is 1.05 for both FCAW and SAW specimens.

It is postulated by Miazga and Kennedy that the prediction models proposed by Miazga and Kennedy (1986, 1989) might apply to double fillet T-joints in tension. The predicted fracture for such joints is 22.5° to the axis of the stem of the Tee and the weld strength would be at least 1.34 times the longitudinal value.

Ng *et al.* (2002) tested six cruciform specimens made with E70T-4 and E70T7-K2 electrodes. The test results showed that transverse fillet welds in a cruciform configuration tend to provide both lower weld strength and lower ductility than transverse welds in a lapped splice connection.

### 2.4 Load Capacity of Joints with Multiple Orientation Fillet Welds (MOFW)

Ligtenberg (1968) reported 223 MOFW connections loaded concentrically and 54 specimens loaded with out-of-plane eccentricity. The results showed that the ratio of the area of transverse welds to that of longitudinal welds was the most critical factor that affected the strength of an MOFW connection. A statistical analysis of the test results

indicated that less than 100 percent of the capacity of the transverse and longitudinal welds was developed in a MOFW.

Based on the observation that longitudinal welds have more ductility than transverse welds, Kato and Morita (1969) proposed a participation factor for the contribution of the longitudinal welds to the capacity of a MOFW joint. The contribution factor, $\mu$, which represents the fraction of the longitudinal weld strength that is developed in a MOFW joint, is given as:

$$\mu=0.788+0.065/z, \quad 0.28 \leq z \leq 3.6 \tag{2.2}$$

where z is the ratio of leg size of longitudinal welds to that of transverse welds in the MOFW joint. Equation (2.2) was used to predict the strength of the test specimens from the international test series of Ligtenberg (1968). The ratio of the tested to predicted capacity was 1.007 for St.37 steel specimens and 1.023 for St.52 steel specimens.

Callele *et al.* (2005) expanded the research program of Ng *et al.* (2002) and Deng *et al.* (2003) to include MOFW joints to investigate whether the least ductile segment in a concentrically loaded MOFW connection can deform sufficiently to develop the full strength of the more ductile segments. A total of 31 double lapped joints that combined transverse welds with either longitudinal or 45° welds were tested. Complementary tests, including nine longitudinal and three transverse fillet welds, were conducted to define the load–deformation curves for fillet welds. The parameters considered in the MOFW specimen design were: (1) fillet weld leg size, (2) number of weld passes, (3) weld continuity at the corners, (4) weld length, and (5) stress state of the connection plates, which is characterized by the plates remaining elastic throughout the test or the plates yielding. Callele *et al.* (2005) proposed the following equation to calculate the capacity of the various segments of a MOFW:

$$\text{Segment Capacity}=P_\theta \, CRF(\theta) \tag{2.3}$$

where $P_\theta$ is the capacity of the weld segment predicted by equation (2.1), $CRF(\theta)$ is the reduction factor, which accounts for the fact that the segment strength may not be fully mobilized. For a MOFW joint with combined longitudinal ($\theta=0°$) and transverse ($\theta=90°$) fillet welds, $CRF(0°) = 0.85$ and $CRF(90°) = 1.0$. The capacities of tested MOFW

specimens were predicted using equation (2.3) and the test-to-predicted ratio was 0.89. However, a reliability analysis showed the safety index is acceptable for a resistance factor of 0.67, as specified in CSA-S16-01.

**2.5 Effects of Weld Size and Length on Fillet Weld Strength**

Ligtenberg (1968) examined the effect of weld size on the strength of connections with transverse welds only and longitudinal welds only. Within the limits of the weld throat dimensions tested, i.e., for weld throats between 3 and 10 mm, with a rather small weld length, the throat size had no significant effect on the strength. However, similar tests by Bornscheuer and Feder (1966) on 35 specimens welded with rutile electrodes showed that the weld size effect on weld strength was significant. The unit strength of 12 mm longitudinal fillet welds was about 35% smaller than that of 4 mm welds. The strength of 12 mm transverse fillet welds was about 20% lower than that of 4 mm welds. Results of Bornscheuer and Feder (1966) also demonstrated that the length of longitudinal fillet welds (length-to-size ratio of 25, 50, 75, and lengths varying from 100 mm to 300 mm) had no influence on the strength.

Kato and Morita (1969) performed tests similar to those presented by Ligtenberg (1968). In their tests, the weld leg size ranged from 5 mm to 40 mm for transverse welds and from 5 mm to 22 mm for longitudinal welds. The strength was calculated on the measured failure area. Kato and Morita concluded that the average maximum strength of fillet welds was not affected by the size of weld within the large range of leg sizes examined.

Higgins and Preece (1969) investigated the effect of weld length upon weld strength. The weld leg size was 6.35 mm (1/4 in.) and the length varied from 6 to 16 times the weld size. Test results showed the strength increased slightly with the increasing length.

Pham (1981) investigated the effect of weld size upon the weld strength by testing welds with in-plane load eccentricity. The nominal weld leg sizes were 5 mm, 10 mm and 16 mm. The other factors considered in specimen design were the weld length and

magnitude of eccentricity. Pham (1981) found that the unit strength of small welds was larger than that of large welds.

Pham (1983a) investigated the effect of weld size on the strength of fillet welds using IIW-recommended cruciform specimens for FCAW and SAW processes. The results showed that the size effect was most dominant in FCAW for welds up to 8 mm measured at the throat. For larger welds there was no further reduction. For SAW specimens the size effect was more gradual but covered the whole range of weld sizes investigated in the test series. In a separate investigation, Pham (1983b) confirmed the observations of the earlier investigation using Werner specimens in which the welds are loaded longitudinally.

Bowman and Quinn (1994) tested specimens with longitudinal and transverse welds with leg sizes of 6.35 mm (1/4 in.), 9.53 mm (3/8 in.) and 12.7 mm (1/2 in.) to investigate the effect of weld size on weld strength. The strength was calculated on the measured rupture areas. For longitudinal specimens, the average strength of 12.7 mm welds was 25% lower than that of 6.35 mm welds. For transverse specimens, the average strength of 12.7 mm specimens was only 4% lower than that of 6.35 mm specimens. It was concluded that a dimple in the exposed weld profile of the 12.7 mm welds due to multiple passes was responsible for the reduced strength.

Ng *et al.* (2002) reported tests of transverse welds prepared with four different FCAW electrodes. The average ratio of the unit strength of the 6.35 mm welds to 12.7 mm welds was 1.26.

Callele *et al.* (2005) analyzed the effect of weld size and number of passes on weld strength using data from Ng *et al.* (2002), Miazga and Kennedy (1989) and their own tests. Generally, the small size welds were found to have higher unit strength with larger scatter. The number of weld passes seemed to have no effect on strength.

Callele *et al.* (2005) also analyzed the effect of longitudinal weld length on weld strength using data from Deng *et al.* (2003), Miazga and Kennedy (1989) and their own tests. The lengths of fillet welds examined were 50, 80, 100 and 150 mm. The 50 mm welds had the

highest average strength and the 100 mm welds had lowest strength, which showed the decrease in strength with an increase of length. However, the 150 mm welds showed higher strength than the 80 mm and 100 mm welds, which made the investigation inconclusive.

## 2.6 Summary

Considerable experimental research has been performed on lapped splice connections with fillet welds loaded at various angles to the weld axis. Researchers generally agree that the weld strength increases as the weld orientation changes from longitudinal to transverse. A reliability analysis of test data from the University of Alberta has shown that the current North American design equations provide an acceptable safety index.

The strength of fillet welds in cruciform joints has not been given much attention yet. The results from a limited number of tests have shown that the strength of cruciform connections tends to be lower than that of transverse welds in lapped splice joints. It is questionable whether the current design equation for weld strength yields an acceptable level of safety when used with cruciform joints.

When fillet welds of different orientations are used in a MOFW connection, the capacity of the more ductile segment cannot be developed fully because of the limited ductility of the least ductile segment. Callele *et al.* (2005) have proposed an equation to consider both the reduction of strength of more ductile weld segments and the increase of strength of the less ductile weld segments compared with that of longitudinal welds. A reliability analysis demonstrated an acceptable level of safety based on limited test results. The applicability of the formula needs to be examined further with a larger number of test results.

Some test results have shown that smaller size fillet welds tend to provide higher unit strengths, no matter whether the strength is calculated on the nominal throat area or on the measured fracture area. Therefore, reliability analysis results based on data from tests on small weld sizes (such as 1/4 in.) should be used with caution. No effect of weld length on weld strength was generally observed.

It is therefore concluded that further experimental research on the strength of cruciform connections is required and a reliability analysis on SOFW and MOFW joints based on a larger data pool is desirable.

# CHAPTER 3

# EXPERIMENTAL PROGRAM AND RESULTS

## 3.1 Introduction

A review of the literature on fillet weld research showed that most experimental programs have used double lap joints, with limited tests on cruciform connections. Because of the more severe root notch orientation in cruciform specimens, it is possible that the strength and ductility of fillet welds in joints of that configuration might be significantly lower than the strength and ductility of double lapped joints. Therefore, an experimental program was designed to investigate the strength and ductility of fillet welds in cruciform connections in order to expand the database of test results on concentrically loaded fillet weld connections. This represents the fourth phase of an ongoing research program on welded joints conducted at the University of Alberta. Phase 1 included tests on transverse welds conducted by Ng *et al.* (2002), phase 2 refers to the test program by Deng *et al.* (2003) and phase 3 refers to the work of Callele *et al.* (2005). The tests presented in this chapter were conducted by Mr. Andre Blanchard and Mr. Derek Kramar, under the supervision of Mr. Logan Callele.

## 3.2 Test Parameters

The factors considered in the design of the test matrix are: connection configuration (*i.e.* cruciform connection vs. lapped splice specimens from previous phases of the research program), welding electrode classification, fillet weld size, main plate stress condition, and test temperature. The phase 4 test matrix, including four different test cases, is presented in Table 3.1. The test specimens are designated by the letters CNY, indicating a cruciform joint configuration with "non-yielding" plates, i.e., plates designed to remain elastic throughout the tests. The specimens are numbered sequentially from 1 to 12. Each test was repeated three times to assess variability of the test results within one treatment.

The specimens were prepared using the flux-cored arc welding (FCAW) process. Two FCAW filler metals were selected, namely, an E70T-7 filler metal, which has no toughness requirement (AWS, 1995), and an E71T8-K6 filler metal, which has a

toughness requirement of 20 J at –29 °C (AWS, 1998). The nominal tensile strength for both electrodes is 480 MPa (70 ksi) and the actual tensile strength was established using tests on all-weld-metal tension coupons. Three such coupons, with a 50 mm gauge length, were prepared in accordance with the appropriate AWS specification (AWS, 1995, 1998) from each wire spool. The results of six coupon tests are presented in Table 3.2 and the stress versus strain curves from each tension coupon are presented in Appendix A.

The steel plates used for the fabrication of the test specimens conformed to the requirements of ASTM A572 Grade 50 and CSA G40.21 350W. This grade of steel is suitable for welding but has no toughness requirement. All specimens were fabricated with plates from the same heat.

The test results from phases 1 to 3 indicated that weld size has a significant effect on the unit strength of fillet welds. Test specimens with a weld size of 6.4 mm showed a higher unit strength than 12.7 mm welds. Since the six pilot cruciform specimens in phase 1 had a leg size of 6.4 mm, all the test specimens from the current phase were made with (nominally) 12.7 mm welds.

Another factor considered in specimen design is the average stress level in the plates during testing. Test results from Ligtenberg (1968) indicated that stress level in the plates did not have a significant effect on fillet weld strength. Callele *et al.* (2005) examined the test results from phases 1 and 3 and those of Miazga and Kennedy (1989) and found that plate yielding before weld fracture may increase the weld ductility, but has negligible effect on weld strength. The plates used in this phase of the test program were therefore designed to remain elastic.

The effect of low temperature on fillet weld behaviour was also one of the test parameters for this phase of the test program. Six cruciform specimens were tested at -50°C. Unfortunately the specimens did not fail as expected. All the specimens tested at low temperature fractured in the plates. Therefore, the low temperature test results are not included in the analysis presented in Chapters 3 and 4. A discussion of the low temperature tests can be found in Appendix D.

### 3. 3 Specimens Description

The dimensions of the test specimens are shown in Figure 3.1. As depicted in the figure, three 76 mm cruciform test specimens were obtained from each assembly. The assemblies were fabricated so that both sides of the connections were nominally identical. Once the assemblies were fabricated they were inspected visually for weld quality and conformance to the design specifications. Whichever side of the central plate was determined to have better weld quality was taken as the test welds and the other side was reinforced by adding additional weld passes in order to force the failure in the test welds, thus reducing the number of welds that had to be instrumented during testing. The test specimens were prepared from the weld assemblies by water jet cutting, followed by milling.

### 3.4 Pre-Test Measurements

Four types of measurements were made to characterize the fillet weld before testing: main plate leg size (MPL), central plate leg size (CPL), throat dimension (measured at 45°), and length of the two test fillet welds. A description of the weld dimensions measured is shown in Figure 3.2. The MPL and CPL dimensions and the 45° throat dimension were measured at eight locations spaced equally along the two test welds for each test specimen. The devices used for measurement of weld size were described in detail in Callele *et al.* (2005).

A summary of the measured weld sizes is presented in Table 3.3, where the values shown represent the average of eight measurements. The complete set of measurements is reported in Appendix B.

For cruciform specimens, any misalignment of the main plates results in load eccentricity during testing. The eccentricities of the main plates were measured as depicted in Figure 3.3 and the results are presented in Table 3.4. The results show that the maximum eccentricity was only 2.05% of the thickness of main plate.

### 3.5 Instrumentation and Test Procedure

The cruciform specimens were tested in a MTS 6000 universal testing machine and loaded in concentric tension until rupture of the fillet welds or plates occurred. The specimens were oriented so that the weld axis was horizontal and the test welds were positioned below the reinforced welds. This orientation facilitated the instrumentation of the specimens with linear variable differential transformers (LVDTs). The overall test setup and instrumentation for the specimens are depicted in Figure 3.4.

Special LVDT brackets were designed in phase 1 to measure the deformation of the test welds during loading. The LVDTs were mounted on the test specimens as shown in Figure 3.4. Two hardened steel anchors used to support one end of the mounting bracket were set in two light punch marks made on the base plates at the toe of the welds. These punch marks ensured that the anchors of the brackets remained in place during the test. The rear of each bracket was fitted with two rollers to stabilize the assembly while at the same time eliminating longitudinal restraint. The brackets were kept anchored to the punch marks during the test using rubber bands wrapped around the specimens. The gauge length over which the weld deformations were measured was the distance between the punch marks and the face of the central plate. The punch marks were placed as close as possible to the toe of the weld so that the amount of plate deformation captured within the gauge length was kept to a minimum. The gauge length used for strain calculations was taken as the average weld leg size within the instrumented weld segment.

For specimens CNY-6, 7, 8, 10, 11, 12, electrical resistance strain gauges were used to measure the strains at the edges of the test specimens, near the weld toe. The strain gauge arrangement is depicted in Figure 3.5. These strain gauges were used to assess the amount of load eccentricity both in the in-plane and in the out-of-plane directions.

The specimens were loaded quasi-statically under displacement control. The load and displacements were recorded in real time during the tests. Static load values were acquired by maintaining a constant deformation for about five minutes. The tests were terminated when one of the test welds ruptured. The instrumentation was then removed

and the specimen was loaded until both test welds had ruptured so that the weld fracture surfaces could be inspected.

### 3.6 Main Plates Misalignment Second Order Effects

Although precautions were taken, fabrication imperfections in the test specimens were unavoidable. Both an angular misalignment and an offset of the axis of the main plates (see measurement 1 and 2 in Figure 3.3 for example) cause bending of the main plates and affect the stresses in the welds during the test. Neglecting the small offsets, the relationship between the maximum bending stress in the plate, $\sigma_b$, resulting from the second order effects, and the tensile stress, $\sigma_t$, caused by the axial force can be estimated by the following equation if the plates are known to remain elastic and the test machine grips are considered pinned:

$$\sigma_b/\sigma_t = \frac{6e}{h} \tag{3.1}$$

where e is the eccentricity of the applied load at the section of interest and h is the dimension of the cross-section perpendicular to the bending axis, as shown in Figure 3.6. The value of $\sigma_b / \sigma_t$ for the six specimens tested at room temperature was analyzed and the results are summarized in Table 3.5. The load eccentricity used in the calculations is the maximum of the four measurements for each specimen as presented in Table 3.4 (i.e., the maximum of L1, L2, L5, and L6). A positive eccentricity causes an increase in tensile stress on the front face of the test specimen as shown in Figure 3.6. The section height (main plate thickness), h, was 50.8 mm.

Table 3.5 indicates that the bending stress on the surface of main plates could be as high as 11% of the tensile stress during the tests. This means that one of the two welds would potentially carry more load than the other weld. However, this observation is based on the assumption that the material remains elastic throughout the test, which was not the case. Yielding of a weld segment would cause a redistribution of the load carried by each weld segment, thus reducing the eccentricity effect. In fact, the fractured welds were not always at the face with higher tensile strains, but were always at the face having the least

weld throat area. This result indicates that in reality the bending effect caused by the eccentricities was not as large as is implied by Table 3.5.

The strain measurements from the six specimens tested at room temperature are presented in Appendix C. Figures C14 to C19 show plots of the normalized load, $P/P_u$, as a function of the normalized strain, $\varepsilon/\varepsilon_y$.

Figures C20 to C25 present plots of the strain ratio, $\varepsilon_b/\varepsilon_t$ as a function of the load ratio, $P/P_u$. Generally, the bending strains reached a peak at about less than 10% of the ultimate load and then decreased sharply to a value close to zero. The stress concentration caused by the abrupt change in geometry made the strains measured with strain gauges very different from the average strain in the plates and it is likely that localized yielding near the weld toe occurred early causing the forces in the welds to redistribute. Overall, the fabrication imperfections are not considered to have had a significant effect on the behaviour of the specimens.

### 3.7 Cruciform Specimen Capacities

The ultimate static capacity of each specimen tested at room temperature is presented in Table 3.6. The strength of the fillet weld was obtained by dividing the static ultimate load $P_{ST}$ by the throat area of the specimens as measured before testing.

The minimum throat area $A_{throat}$ of each segment is a function of the measured weld leg size on the main plate, MPL, and on the central plate, CPL, and the weld length. The definition of MPL, CPL and minimum throat dimension (MTD) for a typical fillet weld cross-section is illustrated in Figure 3.2. The minimum throat dimension (MTD) is the shortest distance from the root of the fillet weld to the hypotenuse of the triangle defined by the two legs of the weld. The minimum throat dimension is obtained from:

$$\text{MTD} = \frac{\text{MPL} \times \text{CPL}}{\sqrt{\text{MPL}^2 + \text{CPL}^2}} \tag{3.2}$$

The minimum throat area, $A_{throat}$, is therefore equal to the product of the minimum throat dimension, MTD, and the weld length. The throat area thus obtained ignores the weld root penetration and the weld face reinforcement, if any. The total throat area is calculated differently depending on the number of fractured welds. If only one weld fractured, the total throat area is taken as twice the minimum throat area of the fractured weld. This, in effect, assumes that half of the applied load was carried by the fractured weld. If both welds fractured simultaneously, the throat area is taken as the sum of the minimum throat areas of the two welds.

The specimens were loaded quasi-statically under displacement control. The load and displacements were recorded in real time during the tests. Static load values were acquired by maintaining a constant deformation for about five minutes and the upper load is the extreme large value and the lower load is the extreme small value within the five minute maintenance of the deformation. The static drop is the difference between the upper and lower load. The ultimate load is the extreme large value of load during the entire loading process. The ultimate load may occur within the last five minute maintenance of deformation or after. The static load reported in Table 3.6 is the one recorded near the ultimate load.

### 3.8 Weld Strains Calculated from Deformations Measured with LVDTs

The weld segment deformations and the calculated strains at the ultimate load and at fracture of specimens tested at room temperature are presented in Table 3.7. The weld strains in the direction of applied load are obtained by dividing the measured weld deformation, $\Delta$, by the average main plate leg (MPL) dimension, $d^*$.

The measured deformation $\Delta$ is reported differently depending on the number of fractured welds. If only one weld fractured, the deformation is taken as the average deformation from the two LVDTs mounted on the fractured weld. Otherwise, the deformation is taken as the average of the four LVDT measurements on the two test welds. The response curves for the specimens tested at room temperature are presented in Appendix C.

### 3.9 Effect of Root Notch Orientation on Weld Strength

The normalized $P_{ST}/A_{throat}$ values presented in Table 3.8 were obtained by dividing $P_{ST}/A_{throat}$ by the measured weld metal tensile strength for the corresponding spool of filler metal. The normalized strength of cruciform specimens is compared with that of lapped splice specimens with transverse welds from phases 1 and 3. These results are tabulated in Tables 3.8a through 3.8d and presented graphically in Figures 3.7a to 3.7d. Each of the figures indicates both the range of values and the mean for a particular set of variables.

Table 3.8a compares the normalized strengths for the lapped splice joint configuration to those obtained from cruciform specimens with a leg size of 12.7 mm and fabricated using E70T-7 welding electrodes. The normalized strengths are plotted in Figure 3.7a. The ratio of the mean normalized strength for cruciform joints to that of lapped splice specimens is 0.81. Table 3.8b and Figure 3.7b present a similar comparison for test specimens with a leg size of 12.7 mm and E71T8-K6 filler metal. The ratio of the mean normalized strength for cruciform joints to that of lapped splice specimens is 0.70. The results indicate that the strength of cruciform joints is significantly lower than that of equivalent lapped splice joints.

Table 3.8c presents a comparison between the normalized strength for lapped splice joints and cruciform joints for 6.4 mm welds and E70T-4 welding electrode classification from phase 1 of the University of Alberta weld test program. The range of the normalized strength is depicted in Figure 3.7c. The ratio of the mean normalized strength for cruciform joints to that of lapped splice joint specimens is 1.01. A similar comparison between cruciform joints and lapped splice joints made with 6.4 mm welds of E70T7-K2 filler metal is presented in Table 3.8d and Figure 3.7d. In this case, the ratio of the mean normalized strength of cruciform joints to that of lapped splice joints is 0.87. The results indicate that the strength of cruciform joints is equal to or lower than that of lapped splice joints with 6.4 mm weld size.

The strength ratios presented in Tables 3.8a to 3.8d are summarized in Table 3.9. The comparisons indicate that the root notch orientation in the cruciform specimen results in

lower fillet weld strength and the magnitude of the strength reduction is affected by the leg size and the toughness requirement of the electrodes. A larger strength reduction is observed with larger weld size and electrodes with toughness requirement. The most severe situation is the fillet weld with a leg size of 12.7 mm and a welding electrode with toughness requirements, for which a strength reduction of almost 30% was observed.

### 3.10 Effect of Root Notch Orientation on Ductility

The weld strains of cruciform specimens are compared with those of lapped splice specimens tested in phase 1 and phase 4. These results are tabulated in Tables 3.10a through 3.10d.

The weld strains measured in specimens prepared with E70T-7 electrodes and 12.7 mm welds are compared in Table 3.10a. When the steel plates remained elastic during the test for both cruciform and lapped splice specimens, the average strain at ultimate load for cruciform joints was found to be 100% of that of lapped splice specimens and the average strain at fracture of cruciform specimens is 70% of that of lapped splice specimens. However, when the comparison is made between cruciform specimens with elastic plates during the test and lapped splice specimens with yielding plates, the average strain at ultimate load for the cruciform specimens was found to be 22% of that of the lapped splice specimens and the average strain at fracture of the cruciform specimens is 13% of that of the lapped splice specimens.

Table 3.10b indicates that specimens prepared with E71T8-K6 electrodes and 12.7 mm welds have an average strain at ultimate load for the cruciform joints 12% of that of the lapped splice specimens. The average strain at fracture of the cruciform specimens is 35% of that of the lapped splice specimens when the steel plates of lapped specimens yielded during the tests but the steel plates of cruciform specimens remained elastic.

In Table 3.10c, the weld strains measured in specimens prepared with E70T-4 electrode and 6.4 mm welds are compared. The average strain at ultimate load for the cruciform joints was found to be 21% of that of the lapped splice specimens. The average strain at

fracture of the cruciform specimens is 35% of that of the lapped splice specimens when the steel plates yielded during the tests.

A comparison of cruciform and lapped splice specimens prepared with E70T7-K2 electrode and 6.4 mm welds is presented in Table 3.10d. The average strain at ultimate load for the cruciform joints was found to be 8% of that of the lapped splice specimens and the average strain at fracture of the cruciform specimens is 8% of that of the lapped splice specimens when the steel plates yielded during the tests.

The results show that cruciform fillet weld specimens have lower ductility compared with lapped splice specimens. It should be noted that in phase 1 the steel plates of the test specimens yielded before the welds fractured and in phases 3 and 4 the steel plates remained elastic throughout the tests. This difference is another reason for the extent of the reduction in weld ductility of cruciform specimens compared to that of lapped splice specimens.

**Table 3.1** – Test Matrix – Cruciform Specimens

| Weld Metal Classification | E70T–7 | E71T8–K6 | E70T–7 | E71T8–K6 |
|---|---|---|---|---|
| Test Temperature | 20 °C | | - 50 °C | |
| Specimen Designation† | CNY–7,8,10 | CNY–6,11,12 | CNY–1,5,9 | CNY–2,3,4 |

† All specimens were fabricated using three passes.

**Table 3.2** – Mechanical Properties of Weld Metal †

| Electrode | Test ID | Static Yield Strength | | Static Tensile Strength | | Modulus of Elasticity | | Rupture Strain | |
|---|---|---|---|---|---|---|---|---|---|
| | | Test | Mean | Test | Mean | Test | Mean | Test | Mean |
| | | (MPa) | (MPa) | (MPa) | (MPa) | (MPa) | (MPa) | (%) | (%) |
| E71T8–K6 | 203–1 | 393 | 383 | 495 | 489 | 195000 | 197000 | 29.8 | 30.2 |
| | 203–2 | 367 | | 484 | | 196000 | | 31.6 | |
| | 203–3 | 389 | | 488 | | 200000 | | 29.3 | |
| E70T–7‡ | 103–1 | 418 | 420 | 568 | 569 | 197000 | 195000 | 8.3 | 11.0 |
| | 103–2 | 431 | | 566 | | 196000 | | 9.0 | |
| | 103–3 | 410 | | 573 | | 193000 | | 15.6 | |

† The strength and strain are expressed as engineering stress and stain.

‡ The test results for this electrode were also reported by Callele *et al.* (2005).

**Table 3.3** – Summary of Pre-Test Weld Measurements

| Specimen | Front Face | | | | | | Back Face | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MTD (mm) | $A_{throat}$ ($mm^2$) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MTD (mm) | $A_{throat}$ ($mm^2$) |
| CNY–1 | 12.87 | 10.31 | 9.72 | 72.4 | 8.05 | 582.5 | 11.85 | 9.85 | 9.84 | 72.4 | 7.58 | 548.6 |
| CNY–2 | 11.89 | 12.67 | 10.85 | 76.3 | 8.67 | 661.8 | 11.50 | 11.42 | 11.01 | 76.3 | 8.10 | 618.2 |
| CNY–3 | 12.90 | 11.98 | 12.12 | 76.3 | 8.77 | 669.8 | 13.49 | 10.71 | 11.61 | 76.3 | 8.39 | 640.2 |
| CNY–4 | 14.97 | 11.63 | 12.28 | 76.3 | 9.18 | 700.8 | 13.51 | 10.79 | 11.27 | 76.3 | 8.43 | 643.5 |
| CNY–5 | 11.46 | 11.60 | 9.39 | 72.4 | 8.15 | 590.6 | 12.64 | 9.06 | 9.62 | 72.4 | 7.36 | 533.4 |
| CNY–6 | 13.15 | 10.71 | 11.51 | 76.3 | 8.30 | 633.6 | 11.98 | 12.64 | 11.83 | 76.3 | 8.69 | 663.5 |
| CNY–7 | 12.81 | 9.54 | 8.95 | 72.5 | 7.65 | 554.6 | 12.13 | 9.76 | 9.41 | 72.4 | 7.60 | 550.7 |
| CNY–8 | 13.50 | 10.15 | 10.36 | 72.4 | 8.11 | 587.5 | 13.10 | 10.23 | 9.76 | 72.4 | 8.06 | 584.1 |
| CNY–9 | 13.48 | 10.40 | 10.76 | 72.4 | 8.23 | 596.4 | 11.91 | 11.65 | 9.94 | 72.4 | 8.33 | 603.1 |
| CNY–10 | 11.91 | 11.55 | 9.82 | 72.4 | 8.29 | 600.1 | 11.47 | 9.63 | 9.39 | 72.3 | 7.37 | 533.4 |
| CNY–11 | 12.25 | 11.76 | 10.78 | 76.3 | 8.48 | 647.1 | 11.90 | 12.17 | 10.83 | 76.3 | 8.51 | 649.0 |
| CNY–12 | 11.82 | 11.86 | 10.87 | 76.3 | 8.37 | 638.7 | 11.06 | 12.49 | 10.26 | 76.3 | 8.28 | 631.8 |

**Table 3.4** – Measured Eccentricities in the Cruciform Specimens

| specimen | L1* (mm) | L2 (mm) | L3 (mm) | L4 (mm) | (L1/h†)×100 (%) | (L2/h)×100 (%) | L5 (mm) | L6 (mm) | L7 (mm) | L8 (mm) | (L5/h)×100 (%) | (L6/h)×100 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CNY–1 | 0.533 | 0.178 | 343 | 342 | 1.05 | 0.35 | 0.457 | 0.254 | 341 | 344 | 0.90 | 0.50 |
| CNY–2 | 0.432 | 0.000 | 347 | 338 | 0.85 | 0.00 | 0.406 | 0.076 | 342 | 343 | 0.80 | 0.15 |
| CNY–3 | -0.788 | -0.914 | 337 | 349 | -1.55 | -1.80 | -0.686 | -0.838 | 340 | 343 | -1.35 | -1.65 |
| CNY–4 | -0.813 | -0.889 | 336 | 349 | -1.60 | -1.75 | 0.940 | 1.041 | 333 | 352 | 1.85 | 2.05 |
| CNY–5 | 0.483 | 0.686 | 343 | 341 | 0.95 | 1.35 | 0.483 | 0.635 | 335 | 350 | 0.95 | 1.25 |
| CNY–6 | 0.787 | 0.889 | 338 | 346 | 1.55 | 1.75 | 0.737 | 0.838 | 339 | 346 | 1.45 | 1.65 |
| CNY–7 | 0.584 | 0.089 | 342 | 343 | 1.15 | 0.18 | 0.533 | 0.152 | 347 | 338 | 1.05 | 0.30 |
| CNY–8 | -0.635 | -0.178 | 337 | 347 | -1.25 | -0.35 | -0.673 | 0.000 | 348 | 335 | -1.32 | 0.00 |
| CNY–9 | -0.559 | -0.559 | 337 | 348 | -1.10 | -1.10 | -0.533 | -0.686 | 344 | 341 | -1.05 | -1.35 |
| CNY–10 | 0.559 | 0.813 | 348 | 337 | 1.10 | 1.60 | 0.635 | 0.813 | 337 | 348 | 1.25 | 1.60 |
| CNY–11 | 0.508 | 0.102 | 337 | 348 | 1.00 | 0.20 | 0.533 | 0.178 | 340 | 344 | 1.05 | 0.35 |
| CNY–12 | -0.406 | -0.102 | 335 | 349 | -0.80 | -0.20 | -0.508 | -0.152 | 346 | 338 | -1.00 | -0.30 |
| maximum | -0.813 | -0.914 | 348 | 349 | -1.60 | -1.80 | 0.940 | 1.041 | 348 | 352 | 1.85 | 2.05 |

* See Figure 3.3 for a definition of the measured eccentricities.

† h = 50.8 mm (thickness of main plate).

**Table 3.5** – Bending Effect on Cruciform Specimens

| Specimen | Maximum Eccentricity (mm) | Bending Effect $\sigma_b / \sigma_t$ † | Face Fractured | $A_{throat}$ ($mm^2$) | |
|---|---|---|---|---|---|
| | | | | Front Face | Back Face |
| CNY–6 | 0.889 | 0.11 | Front | 634 | 663 |
| CNY–7 | 0.584 | 0.07 | Back | 555 | 551 |
| CNY–8 | -0.673 | -0.08 | Back | 587 | 584 |
| CNY–10 | 0.813 | 0.10 | Back | 600 | 533 |
| CNY–11 | 0.533 | 0.06 | Back | 647 | 649 |
| CNY–12 | -0.508 | -0.06 | Back | 639 | 632 |

† A positive effect implies high tension on the front face.

**Table 3.6** – Summary of Test Capacities Obtained at Room Temperature

| Specimen | Electrode | $P_u$ Ultimate Load (kN) | Static Drop (kN) | | | $P_{ST} = P_u - \Delta P$ (kN) | Total Area $A_{throat}$ (mm$^2$) | $P_{ST} / A_{throat}$ (MPa) | Average $P_{ST} / A_{throat}$ | Weld Failed |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | upper | lower | ΔP | | | | | |
| CNY–7 | E70T–7 | 606 | 586 | 577 | 8 | 597 | 1109 | 539 | 588 | Front |
| CNY–8 | | 723 | 713 | 702 | 11 | 712 | 1168 | 609 | | Back |
| CNY–10 | | 667 | 658 | 647 | 11 | 656 | 1067 | 615 | | Back |
| CNY–6 | E71T8–K6 | 770 | 762 | 750 | 12 | 759 | 1327 | 572 | 576 | Back |
| CNY–11 | | 760 | 754 | 743 | 11 | 749 | 1298 | 577 | | Back |
| CNY–12 | | 744 | 741 | 727 | 13 | 731 | 1264 | 578 | | Back |

**Table 3.7** – Ultimate and Fracture Weld Deformations and Strains

| Specimen | Deformation (mm) | | Strain (mm/mm) | | | |
|---|---|---|---|---|---|---|
| | Ultimate $\Delta_{ult}$ | Fracture $\Delta_f$ | $\Delta_{ult} / d^*$ | Mean of $\Delta_{ult} / d^*$ | $\Delta_f / d^*$ | Mean of $\Delta_f / d^*$ |
| CNY–7 | 0.30 | 2.04 | 0.0234 | 0.025 | 0.0797 | 0.062 |
| CNY–8 | 0.48 | 0.70 | 0.0363 | | 0.0535 | |
| CNY–10 | 0.17 | 0.62 | 0.0145 | | 0.0538 | |
| CNY–6 | 0.27 | 1.19 | 0.0224 | 0.034 | 0.0990 | 0.091 |
| CNY–11 | 0.45 | 0.94 | 0.0379 | | 0.0789 | |
| CNY–12 | 0.47 | 1.04 | 0.0422 | | 0.0938 | |

**Table 3.8a** – Comparison of Fillet Weld Strength (12.7 mm, E70T–7)

| Specimen | Joint Configuration | Phase | Electrode | Plate Stress | $P_{ST} / A_{throat}$ (MPa) | Normalized ‡ $P_{ST} / A_{throat}$ | Mean | Strength Ratio† |
|---|---|---|---|---|---|---|---|---|
| T25–1 | lapped | 1 | E70T–7 | yield | 780 | 1.29 | 1.28 | 0.81 |
| T25–2 | | | | | 771 | 1.27 | | |
| T25–3 | | | | | 795 | 1.31 | | |
| T26–1 | lapped | 1 | | yield | 822 | 1.36 | | |
| T26–2 | | | | | 836 | 1.38 | | |
| T26–3 | | | | | 807 | 1.33 | | |
| T27–1 | lapped | 1 | | yield | 647 | 1.11 | | |
| T27–2 | | | | | 736 | 1.26 | | |
| T27–3 | | | | | 748 | 1.28 | | |
| T28–1 | lapped | 1 | | yield | 775 | 1.19 | | |
| T28–2 | | | | | 810 | 1.24 | | |
| T28–3 | | | | | 781 | 1.20 | | |
| TNY–1 | lapped | 3 | | elastic | 752 | 1.32 | | |
| TNY–2 | | | | | 740 | 1.30 | | |
| TNY–3 | | | | | 774 | 1.36 | | |
| CNY–7 | cruciform | 4 | | elastic | 539 | 0.95 | 1.03 | |
| CNY–8 | | | | | 609 | 1.07 | | |
| CNY–10 | | | | | 615 | 1.08 | | |

† The strength ratio is the mean normalized strength of cruciform to that of lapped splice connections.

‡ $P_{ST} / A_{throat}$ is normalized against the measured weld metal tensile strength.

**Table 3.8b** – Comparison of Fillet Weld Strength (12.7 mm, E71T8–K6)

| Specimen | Joint Configuration | Phase | Electrode | Plate Stress | $P_{ST} / A_{throat}$ (MPa) | Normalized $P_{ST} / A_{throat}$ | Mean | Strength Ratio |
|---|---|---|---|---|---|---|---|---|
| T31–1 | lapped | 1 | E71T8–K6 | yield | 847 | 1.73 | 1.67 | 0.70 |
| T31–2 | | | | | 822 | 1.68 | | |
| T31–3 | | | | | 870 | 1.78 | | |
| T32–1 | lapped | 1 | | yield | 779 | 1.58 | | |
| T32–2 | | | | | 789 | 1.60 | | |
| T32–3 | | | | | 828 | 1.68 | | |
| CNY–6 | cruciform | 4 | | elastic | 572 | 1.17 | 1.18 | |
| CNY–11 | | | | | 577 | 1.18 | | |
| CNY–12 | | | | | 578 | 1.18 | | |

**Table 3.8c** – Comparison of Fillet Weld Strength (6.4 mm, E70T–4)

| Specimen | Joint Configuration | Phase | Electrode | Plate Stress | $P_{ST} / A_{throat}$ (MPa) | Normalized $P_{ST} / A_{throat}$ | Mean | Strength Ratio |
|---|---|---|---|---|---|---|---|---|
| T4–1 | lapped | 1 | E70T–4 | yield | 982 | 1.84 | 1.87 | 1.01 |
| T4–2 | | | | | 973 | 1.82 | | |
| T4–3 | | | | | 972 | 1.82 | | |
| T5–1 | lapped | 1 | | yield | 998 | 1.87 | | |
| T5–2 | | | | | 943 | 1.76 | | |
| T5–3 | | | | | 993 | 1.86 | | |
| T6–1 | lapped | 1 | | yield | 1175 | 2.20 | | |
| T6–2 | | | | | 1073 | 2.01 | | |
| T6–3 | | | | | 1172 | 2.19 | | |
| T8–2 | lapped | 1 | | yield | 930 | 1.66 | | |
| T8–3 | | | | | 934 | 1.66 | | |
| T9–1 | lapped | 1 | | yield | 1098 | 1.95 | | |
| T9–2 | | | | | 1084 | 1.93 | | |
| T9–3 | | | | | 1111 | 1.98 | | |
| T10–1 | lapped | 1 | | yield | 970 | 1.73 | | |
| T10–2 | | | | | 1049 | 1.87 | | |
| T10–3 | | | | | 952 | 1.69 | | |
| C1–1 | cruciform | 1 | | yield | 1067 | 1.99 | 1.89 | |
| C1–2 | | | | | 1028 | 1.92 | | |
| C1–3 | | | | | 943 | 1.76 | | |

**Table 3.8d** – Comparison of Fillet Weld Strength (6.4 mm, E70T7–K2)

| Specimen | Joint Configuration | Phase | Electrode | Plate Stress | $P_{ST} / A_{throat}$ (MPa) | Normalized $P_{ST} / A_{throat}$ | Mean | Strength Ratio |
|---|---|---|---|---|---|---|---|---|
| T16–1 | lapped | 1 | E70T7-K2 | yield | 936 | 1.58 | 1.84 | 0.87 |
| T16–3 | | | | | 952 | 1.61 | | |
| T17–1 | lapped | 1 | | yield | 1158 | 1.96 | | |
| T17–2 | | | | | 1222 | 2.06 | | |
| T17–3 | | | | | 1180 | 1.99 | | |
| C2–1 | cruciform | 1 | | yield | 997 | 1.68 | 1.59 | |
| C2–2 | | | | | 954 | 1.61 | | |
| C2–3 | | | | | 877 | 1.48 | | |

**Table 3.9** – Summary of Strength Ratio (strength of cruciform joint/strength of lapped splice joint)

| | | Electrode | | | |
|---|---|---|---|---|---|
| | | With toughness requirement | | Without toughness requirement | |
| | | E71T8–K6 | E70T7–K2 | E70T–7 | E70T–4 |
| Leg size (mm) | 12.7 | 0.70 | — | 0.81 | — |
| | 6.4 | — | 0.87 | — | 1.01 |

**Table 3.10a** – Comparison of Fillet Weld Strains (12.7 mm, E70T–7)

| Specimen | Joint Configuration | Phase | Electrode Classification | Plate Stress | Mean of $\Delta_{ult} / d^*$ | Mean of $\Delta_f / d^*$ | Strain Ratio† (Ultimate Load) | Strain Ratio† (Fracture) |
|---|---|---|---|---|---|---|---|---|
| T25–1 | lapped | 1 | E70T–7 | yield | 0.12 | 0.13 | 0.22 | 0.13 |
| T25–2 | | | | | | | | |
| T25–3 | | | | | | | | |
| T26–1 | lapped | 1 | | yield | 0.20 | 0.20 | | |
| T26–2 | | | | | | | | |
| T26–3 | | | | | | | | |
| T27–1 | lapped | 1 | | yield | 0.10 | 0.10 | | |
| T27–2 | | | | | | | | |
| T27–3 | | | | | | | | |
| T28–1 | lapped | 1 | | yield | 0.12 | 0.12 | | |
| T28–2 | | | | | | | | |
| T28–3 | | | | | | | | |
| TNY–1 | lapped | 3 | E70T–7 | elastic | 0.03 | 0.10 | 1.0 | 0.7 |
| TNY–2 | | | | | | | | |
| TNY–3 | | | | | | | | |
| CNY–7 | cruciform | 4 | | elastic | 0.03 | 0.07 | — | — |
| CNY–8 | | | | | | | | |
| CNY–10 | | | | | | | | |

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.

**Table 3.10b** – Comparison of Fillet Weld Strains (12.7 mm, E71T8–K6)

| Specimen | Joint Configuration | Phase | Electrode Classification | Plate Stress | Mean of $\Delta_{ult} / d^*$ | Mean of $\Delta_f / d^*$ | Strain Ratio† (Ultimate Load) | Strain Ratio† (Fracture) |
|---|---|---|---|---|---|---|---|---|
| T31–1 | lapped | 1 | E71T8–K6 | yield | 0.24 | 0.26 | 0.12 | 0.35 |
| T31–2 | | | | | | | | |
| T31–3 | | | | | | | | |
| T32–1 | lapped | 1 | | yield | 0.27 | 0.26 | | |
| T32–2 | | | | | | | | |
| T32–3 | | | | | | | | |
| CNY–6 | cruciform | 4 | | elastic | 0.03 | 0.09 | — | — |
| CNY–11 | | | | | | | | |
| CNY–12 | | | | | | | | |

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.

**Table 3.10c** – Comparison of Fillet Weld Strains (6.4 mm, E70T–4)

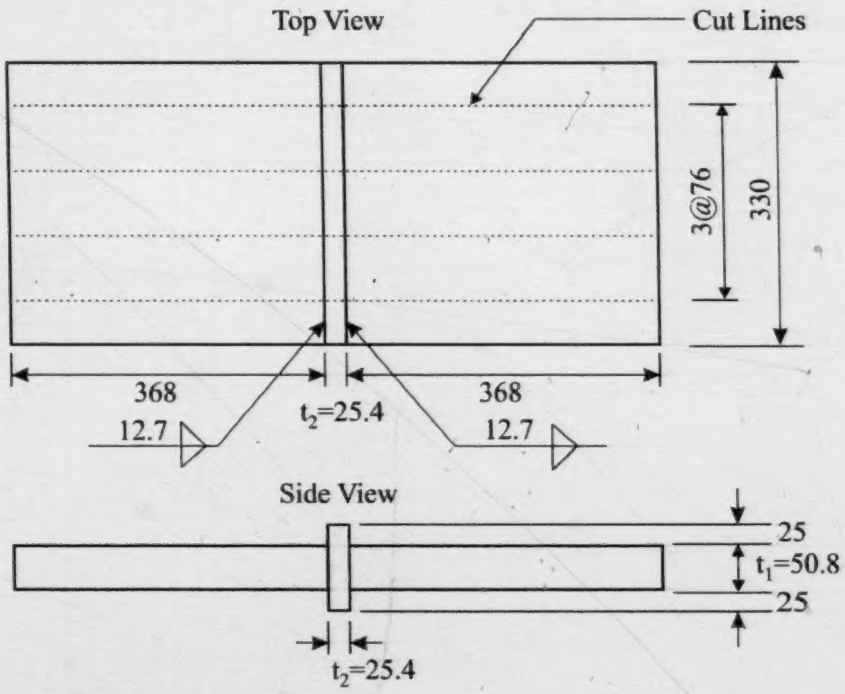
| Specimen | Joint Configuration | Phase | Electrode Classification | Plate Stress | Mean of $\Delta_{ult} / d^*$ | Mean of $\Delta_f / d^*$ | Strain Ratio† (Ultimate Load) | Strain Ratio† (Fracture) |
|---|---|---|---|---|---|---|---|---|
| T4–1 | lapped | 1 | E70T–4 | yield | 0.08 | 0.08 | 0.21 | 0.35 |
| T4–2 | | | | | | | | |
| T4–3 | | | | | | | | |
| T5–1 | lapped | 1 | | yield | 0.09 | 0.09 | | |
| T5–2 | | | | | | | | |
| T5–3 | | | | | | | | |
| T6–1 | lapped | 1 | | yield | 0.16 | 0.16 | | |
| T6–2 | | | | | | | | |
| T6–3 | | | | | | | | |
| T8–2 | lapped | 1 | | yield | 0.21 | 0.23 | | |
| T8–3 | | | | | | | | |
| T9–1 | lapped | 1 | | yield | 0.19 | 0.19 | | |
| T9–2 | | | | | | | | |
| T9–3 | | | | | | | | |
| T10–1 | lapped | 1 | | yield | 0.11 | 0.12 | | |
| T10–2 | | | | | | | | |
| T10–3 | | | | | | | | |
| C1–1 | cruciform | 1 | | yield | 0.03 | 0.03 | — | — |
| C1–2 | | | | | | | | |
| C1–3 | | | | | | | | |

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.

**Table 3.10d** – Comparison of Fillet Weld Strains (6.4 mm, E70T7–K2)

| Specimen | Joint Configuration | Phase | Electrode Classification | Plate Stress | Mean of $\Delta_{ult} / d^*$ | Mean of $\Delta_f / d^*$ | Strain Ratio† (Ultimate Load) | Strain Ratio† (Fracture) |
|---|---|---|---|---|---|---|---|---|
| T16–1 | lapped | 1 | E70T7–K2 | yield | 0.27 | 0.29 | 0.08 | 0.08 |
| T16–2 | | | | | | | | |
| T16–3 | | | | | | | | |
| T17–1 | lapped | 1 | | yield | 0.09 | 0.09 | | |
| T17–2 | | | | | | | | |
| T17–3 | | | | | | | | |
| C2–1 | cruciform | 1 | | yield | 0.03 | 0.03 | — | — |
| C2–2 | | | | | | | | |
| C2–3 | | | | | | | | |

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.




All dimensions are in mm

**Figure 3.1** – Dimensions of Cruciform Test Specimens

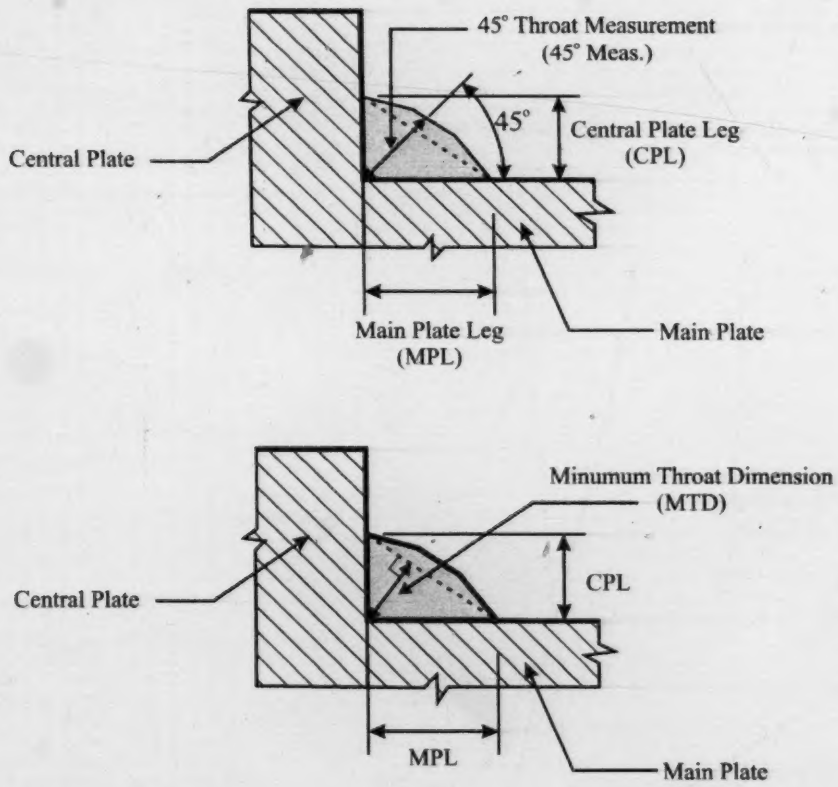
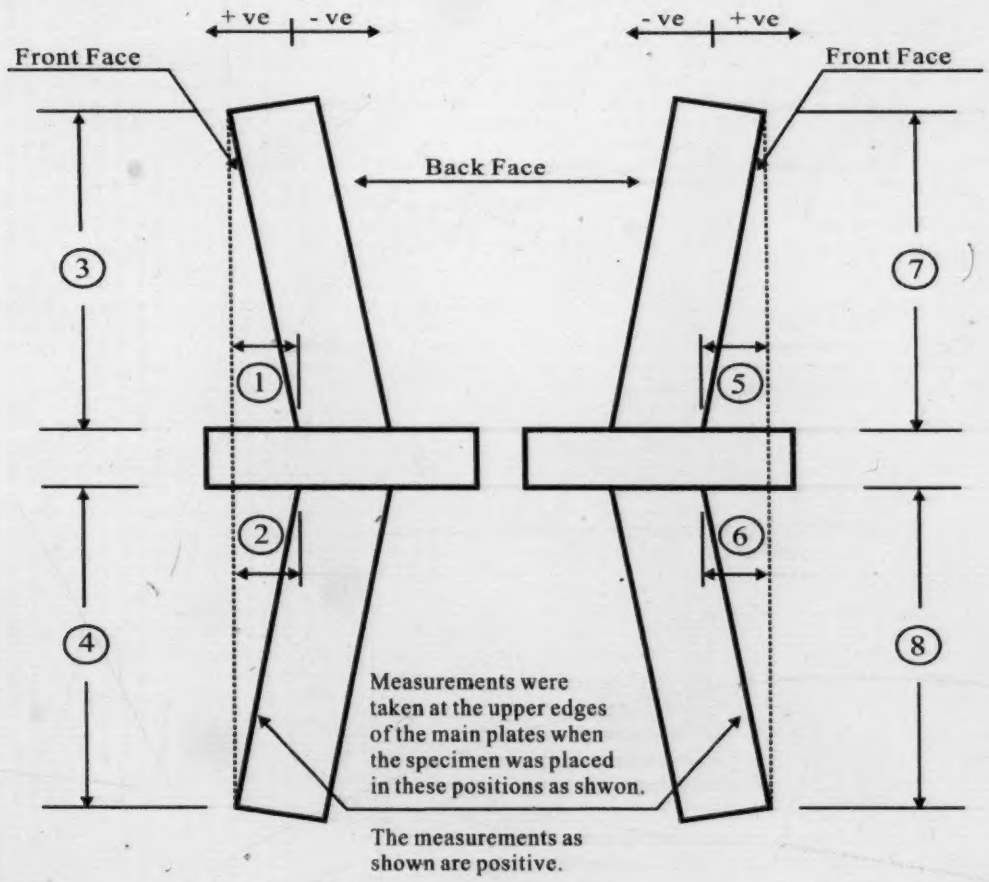
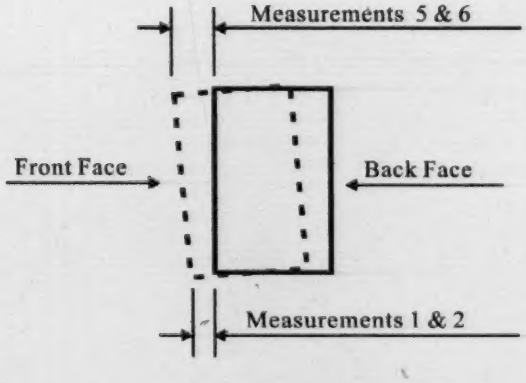



**Figure 3.2** – Definition of Fillet Weld Pre-Test Measurements




**Side View**




**Top View**

**Figure 3.3** – Eccentricity Measurements

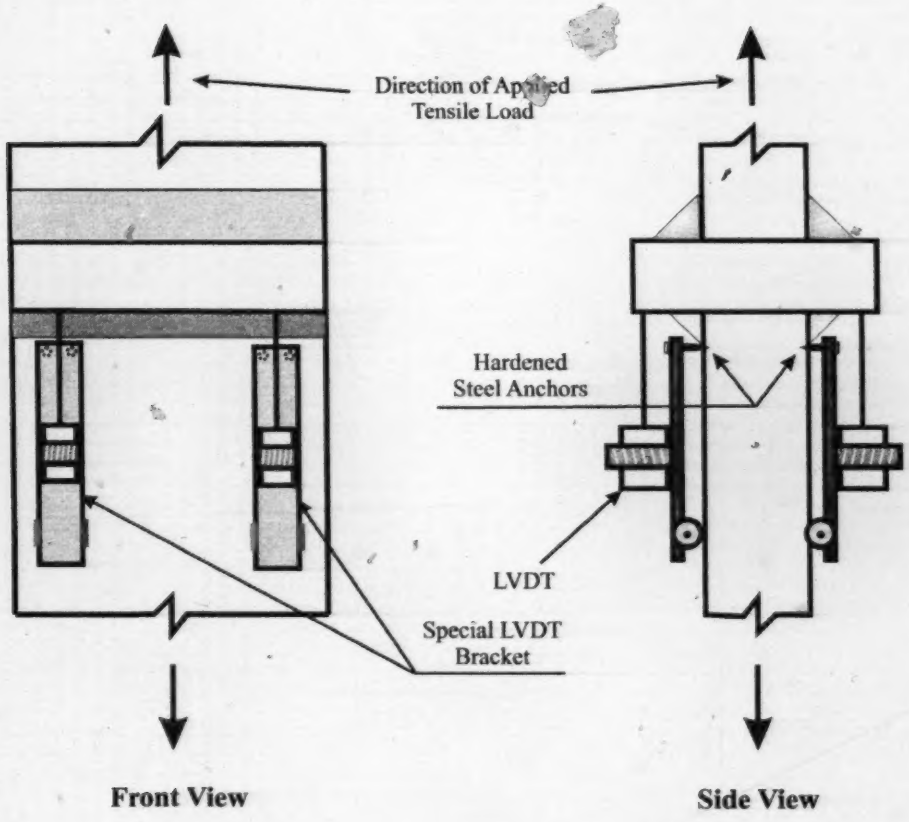
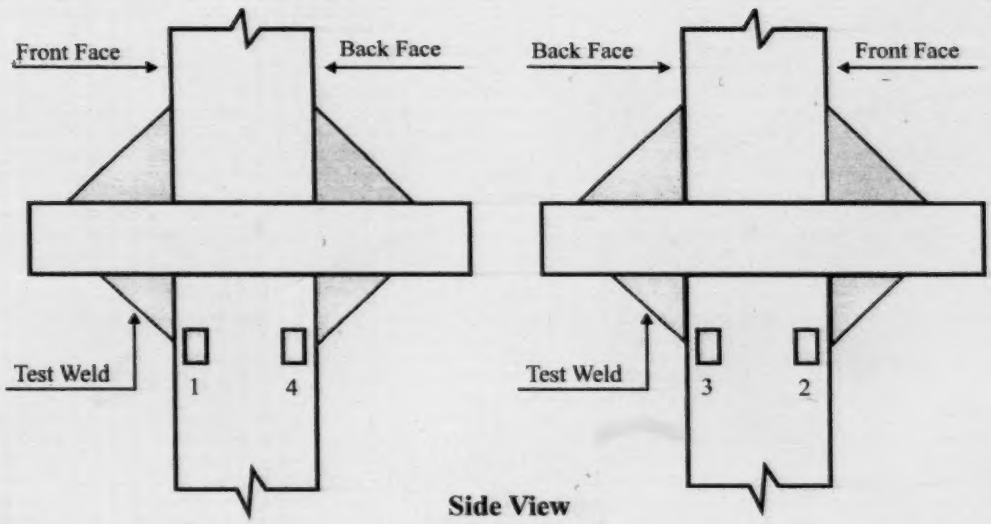
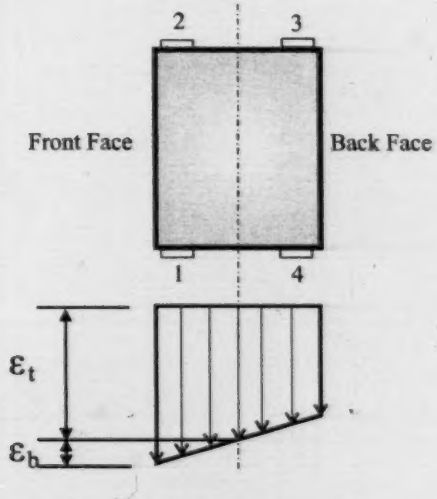



**Figure 3.4** – Weld Deformation Measurements




**Side View**




**Top View and Strains**

**Figure 3.5** – Arrangement of Strain Gauges

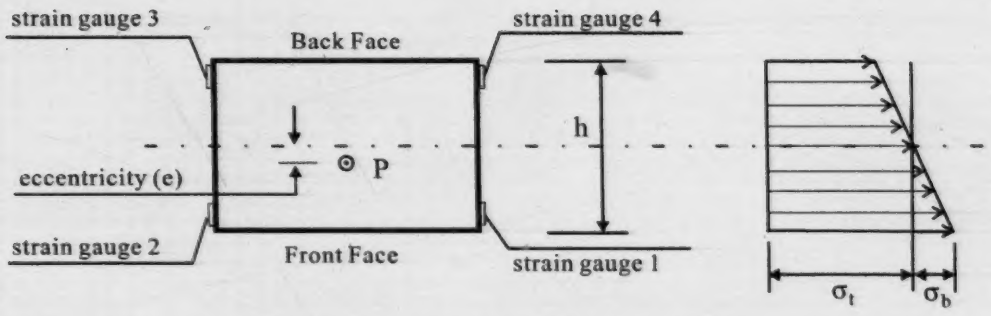
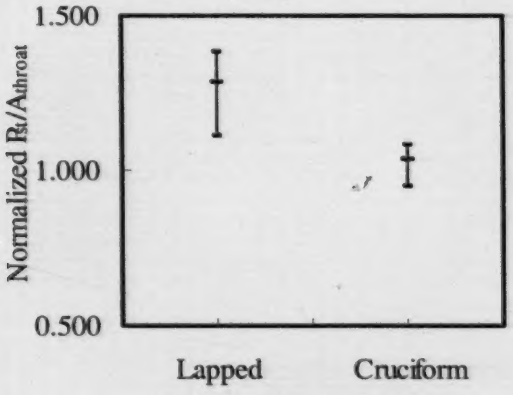
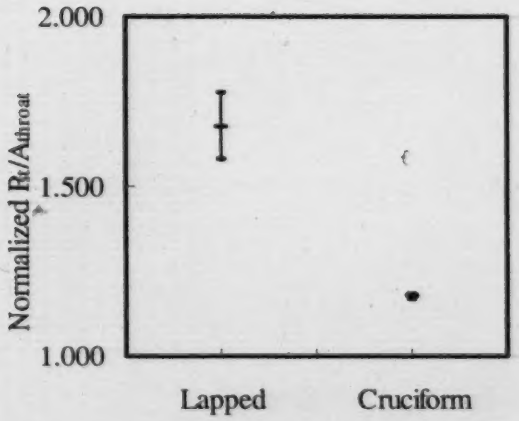



**Figure 3.6** – Load Eccentricity and Bending Effect

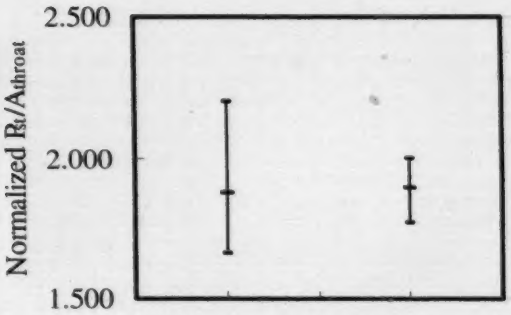



(a) Leg size 12.7mm, E70T-7

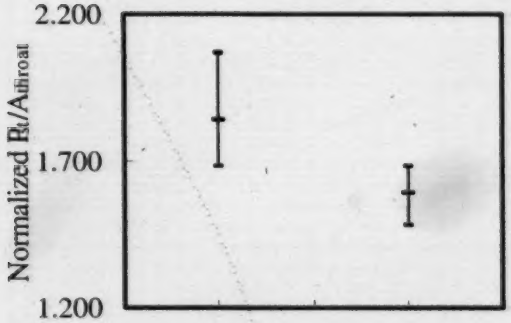



(b) Leg size 12.7mm, E71T8-K6

**Figure 3.7** – Effect of Root Notch Orientation on Weld Strength




(c) Leg size 6.4mm, E70T-4




(d) Leg size 6.4mm, E70T7-K2

**Figure 3.7 (cont.)**

# CHAPTER 4

# ANALYSIS OF TEST RESULTS

## 4. 1 Introduction

To get a better representation of the scatter present in industry, test data from different sources were pooled. About 1160 specimens from 16 test programs were examined. The detailed information about the data sources is given in Appendix E.

The strength equation used for the design of fillet welds in the Canadian design standard, CSA S16.1–01 (CSA 2001), is given as:

$$V_r = 0.67\phi_w A_w X_u (1.00 + 0.50\sin^{1.5}\theta) \qquad (4.1a)$$

where the resistance factor $\phi_w$ is taken as 0.67, $A_w$ is the effective throat area of the weld, $X_u$ is the minimum specified tensile strength of the weld metal, and $\theta$ is the angle between the weld axis and the line of action of the applied load. The numerical modifier 0.67 relates the shear strength of the fillet weld to the tensile strength, $X_u$, of the weld metal.

Similarly, the equation in the ANSI/AISC 360-05 (AISC 2005) is given as:

$$V_r = 0.60\phi A_w F_{EXX} (1.00 + 0.50\sin^{1.5}\theta) \qquad (4.1b)$$

where the resistance factor $\phi$ is taken as 0.75, $A_w$ is the effective throat area of the weld, and $F_{EXX}$ is the tensile strength of the weld metal. The numerical modifier 0.60 relates the shear strength of the weld metal to its tensile strength.

The difference between the observed and the nominal strength of fillet welds results from the variation in the geometric and material properties of the weld segments, as well as from the equation used to predict the fillet weld strength. To assess the safety index associated with Equation 4.1, the bias coefficient for resistance, $\rho_R$, and its coefficient of variation, $V_R$, can be obtained using the following equations:

$$\rho_R = \rho_G \rho_{M1} \rho_{M2} \rho_P \qquad (4.2)$$

$$V_R^2 = V_G^2 + V_{M1}^2 + V_{M2}^2 + V_P^2 \tag{4.3}$$

The geometric bias coefficient, $\rho_G$, which reflects the difference between the nominal and actual fillet weld throat area, can be calculated as the mean value of the ratio of the measured throat dimension (MTD) to 0.707 times of nominal weld leg size, namely,

$$\rho_G = \text{Mean}\left(\frac{\text{MTD}}{0.707 \times (\text{nominal weld leg size})}\right) \tag{4.4a}$$

In addition, the geometric bias coefficient can be calculated as the mean value of the ratio of MTD to the nominal throat dimension, namely,

$$\rho_G = \text{Mean}\left(\frac{\text{MTD}}{\text{nominal throat dimension}}\right) \tag{4.4b}$$

In Equations 4.4a and 4.4b, MTD is taken differently as described in the following three cases, depending on the data available (measured leg or measured throat).

Case 1: when two leg sizes were measured and reported from a test program, MTD is taken as the minimum throat dimension:

$$\text{MTD} = \frac{s_1 \times s_2}{\sqrt{s_1^2 + s_2^2}} \tag{4.4c}$$

where, $s_1$ and $s_2$ are two measured leg sizes.

Case 2: when two leg sizes were measured but only the average of the two leg sizes was reported, MTD is taken as in the following equation:

$$\text{MTD} = 0.707 \times (\text{average of two leg sizes}) \tag{4.4d}$$

Case 3: when only the throat dimension at 45° was measured and reported from a test program, MTD is taken as the measured throat dimension:

$$\text{MTD} = \text{measured throat dimension} \tag{4.4e}$$

Then the measured throat area, $A_{throat}$, can hereafter be calculated as follows:

$$A_{throat} = \text{MTD} \times (\text{weld length}) \tag{4.4f}$$

where MTD is the measured throat dimension as described in the three cases above.

Equations 4.4c and 4.4d neglect the variability of the reinforcement at the weld face and Equations 4.4c, 4.4d and 4.4e all neglect the variability of weld penetration at the root.

The variability of the reinforcement of test specimens from phase 1 through 4 is presented in Section 4.2.1 and Table 4.3. Although Equation 4.4b might on this basis appear to be the more representative quantity, "nominal" throat dimensions are rarely specified now. In all cases, the variability of the weld length is neglected, in part due to a lack of suitable data, and also since this is likely to lead to conservative conclusions due to the tendency of welds to be longer than specified.

The first material bias coefficient, $\rho_{M1}$, is the mean value of the measured to nominal weld metal tensile strength, expressed as:

$$\rho_{M1}=\text{Mean}\left(\frac{\text{Measured Tensile Strength, } \sigma_u}{\text{Specified Tensile Strength, } X_u \text{ or } F_{EXX}}\right) \tag{4.5}$$

where $\sigma_u$ is determined from all-weld-metal tension coupons.

Another source of variation in material strength is related to the relationship between the tensile strength and the shear strength. Equation 4.1a uses a factor 0.67 and Equation 4.1b uses a factor 0.60to convert the tensile strength into shear strength. The measured shear strength to tensile strength ratio can be obtained from longitudinal weld test specimens. The shear strength, $\tau_u$, from test specimens is calculated using the measured throat area, $A_{throat}$. The second material bias coefficient, $\rho_{M2}$, is expressed as:

$$\rho_{M2}=\text{Mean}\left(\frac{\text{Measured Shear Strength, } \tau_u / \text{Measured tensile strength, } \sigma_u}{0.67}\right) \tag{4.6a}$$

for Equation 4.1a, or

$$\rho_{M2}=\text{Mean}\left(\frac{\text{Measured Shear Strength, } \tau_u / \text{Measured tensile strength, } \sigma_u}{0.60}\right) \tag{4.6b}$$

for Equation 4.1b.

The professional factor, $\rho_P$, is the mean value of the test-to-predicted capacity ratio for test specimens with various fillet weld orientations:

$$\rho_p=\text{Mean}\left(\frac{\text{Test Capacity}}{\text{Predicted Capacity}}\right)=\text{Mean}\left(\frac{\text{Test Capacity}}{\tau_u\, A_{throat}(1.00+\sin^{1.5}\theta)}\right) \tag{4.7}$$

The area $A_{throat}$ used in Equation 4.7 is defined in Equation 4.4f. The term $\tau_u$ is the measured shear strength from tests on longitudinal weld specimens prepared using the same filler metal as the test specimens used for other weld orientations within the same program. It is based on the measured throat area, $A_{throat}$.

The variables in Equation 4.3 are the coefficients of variation corresponding to the four bias coefficients described above.

The above discussion is applied to connections with single orientation fillet welds (SOFW). For connections with multiple orientations fillet welds (MOFW), 3 models are used to calculate the capacity of such connections.

Model 1: Callele *et al.* (2005) recommended the following equation to calculate the capacity of weld segments for design:

$$\text{Segment Capacity} = 0.67\phi_w A_w X_u (1.00 + 0.50\sin^{1.5}\theta)\ CRF(\theta) \tag{4.8}$$

where $CRF(\theta)$ is the reduction factor that accounts for the fact that the strength of the most ductile segment of the MOFW connection may not be reached by the time the least ductile segment fractures. For a connection with combined longitudinal ($\theta = 0°$) and transverse ($\theta = 90°$) fillet welds, $CRF(0°) = 0.85$ and $CRF(90°) = 1.0$. The capacity of the connection with longitudinal and transverse welds is the summation of all segment capacities:

$$V_r = c_1\ \phi\ X_u (0.85A_{wl} + 1.5A_{wt}) \tag{4.9}$$

where $c_1$ is equal to 0.67 in CSA S16.1–01 (2001) and 0.60 in ANSI/AISC 360-05 (AISC 2005), $A_{wl}$ is the total throat area of longitudinal welds and $A_{wt}$ is the total throat area of transverse welds.

Model 2: when CSA S16.1–01 (CSA 2001) design Equation 4.1a is used to calculate the capacity of a weld segment, the total capacity of a MOFW connection with both longitudinal and transverse welds can be intuitively calculated as:

$$V_r = c_1\ \phi\ X_u (A_{wl} + 1.5A_{wt}) \tag{4.10}$$

Since no guidelines currently exist in S16.1–01 for the calculation of the strength of MOFW joints, this model ignores the difference in ductility between segments loaded in different directions.

Model 3: when the ANSI/AISC 360-05 (AISC 2005) is applied, the capacity of a MOFW connection with both longitudinal and transverse welds is determined as the greater of:

$$V_r = c_1 \phi F_{EXX} (A_{wl} + A_{wt}) \tag{4.11a}$$

or

$$V_r = c_1 \phi F_{EXX} (0.85A_{wl} + 1.5A_{wt}) \tag{4.11b}$$

The professional factor, $\rho_P$, can be calculated for the above three models with the resistance factor, $\phi_w$ or $\phi$, set to 1.0.

Once the bias coefficient for resistance, $\rho_R$, and the associated coefficient of variation, $V_R$, are obtained, the safety index $\beta$ can be determined from the following equation for the resistance factor, $\phi$, which was originally proposed by Ravindra and Galambos (1978):

$$\phi_w = C \rho_R \exp(-\beta \alpha_R V_R) \tag{4.12}$$

The separation variable, $\alpha_R$, was set to 0.55 as suggested by Ravindra and Galambos (1978). The factor $C$ is an adjustment factor that modifies $\phi$ when $\beta$ is not equal to the safety index used for the evaluation of load factors, which is normally 3.0. The following equation, developed using a procedure proposed by Fisher *et al.* (1978), was used to calculate this factor for a live to dead load ratio of 3.0:

$$C = 0.0078\beta^2 - 0.156\beta + 1.400 \tag{4.13}$$

It should be noted that the above equation is applicable for a range of safety index from 1.5 to 6.0.

## 4.2 Summary of Test Data from Different Sources

### *4.2.1 Geometric Factor, $\rho_G$*

The bias coefficient, $\rho_G$, and the coefficient of variation, $V_G$, for the measured-to-nominal throat dimension collected from literature (see Appendix E) are summarized in Table 4.1. First, the specimens are separated into two groups according to the weld dimension measurement method, namely, specimens with measured throat dimension and specimens with measured leg size. For each group, the geometric factor, $\rho_G$, and the associated coefficient of variation, $V_G$, are calculated. Then, all data are pooled to obtain the mean ratio $\rho_G$ and associated $V_G$. The mean values for the two groups are nearly identical, but the dispersion, as expected, is somewhat greater when the throat measurements are used.

The variations of $\rho_G$ and $V_G$ as a function of the nominal weld leg size are illustrated graphically in Figures 4.1a and 4.1b. The general trend is that the small size welds are more likely to be oversized than large welds and the size of large welds is slightly less variable than the size of small welds. These observations reflect the difficulty of producing small size welds.

It is noted that the data presented in Table 4.1 were all collected from experimental programs. It is also noted that in some test programs, for example those of Ng *et al.* (2002), Deng *et al.* (2003), Callele *et al.* (2005), and the current test program, strict tolerances were set on the weld sizes during fabrication of the test specimens so that fracture of the welds would be most likely to occur rather than fracture of the plates. It is therefore possible that the ratio $\rho_G$ obtained from such data would be smaller than what would be expected in practice, thus making the results of a reliability analysis based on this data conservative. It should also be noted that the value of $V_G$ might be slightly underestimated for the same reason.

For the current test specimens and those from Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al.* (2005), the geometric factor $\rho_G$ was calculated using Equation 4.4a and MTD was calculated using Equation 4.4c, which accounts for the unequal leg sizes.

Of all the research compiled in this report from the literature, only that of Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al.* (2005) reported both measured leg and throat dimensions (see Section E.12), thereby giving an opportunity to assess directly the degree of face reinforcement in the fillet weld as deposited. To this end, two ratios based on these measurements are defined as follows:

$$\alpha_1 = \text{Mean}\left(\frac{45^\circ \text{ Meas}}{\text{MTD}}\right) \tag{4.14a}$$

$$\alpha_2 = \text{Mean}\left(\frac{45^\circ \text{ Meas}}{0.707 \times (\text{average of MPL and LPL})}\right) \tag{4.14b}$$

The measurements of MPL, LPL, and 45° Meas, the calculated MTD, and the ratios $\alpha_1$, $\alpha_2$, and $\rho_G$ for the specimens of Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005) (Phases 1 to 3 of this research program) are presented in Tables E12.1 through E12.5. The same analysis for specimens from the current test program (Phase 4) is presented in Table 4.2. The results are summarized in Table 4.3.

The overall mean values for $\alpha_1$ and $\alpha_2$ from Phases 1 to 4 are 1.12 and 1.11, respectively, with corresponding coefficients of variation of 0.088 and 0.090, indicating that the throat dimension from the weld root to the weld face is about 10% greater than the theoretical throat for these groups of specimens.

### *4.2.2 Material Factor, $\rho_{M1}$*

The material factor $\rho_{M1}$ and the corresponding coefficient of variation, $V_{M1}$, collected from the literature are summarized in Table 4.4. The variation of $\rho_{M1}$ as a function of the nominal tensile strength of the electrode is shown in Figure 4.2. For the data available,

there seems to be no correlation between $\rho_{M1}$ and the nominal filler metal tensile strength.

The variation in $\rho_{M1}$, expressed as a range of two standard deviations about the mean value for each test program presented in Table 4.4 is plotted in Figure 4.3 to show the variability of the ratio $\rho_{M1}$ of those tests that span from as early as 1970s to the most recent as the year of 2005.

### *4.2.3 Material Factor, $\rho_{M2}$*

The material factor $\rho_{M2}$ and the associated coefficient of variation $V_{M2}$ are associated with the shear strength, $\tau_u$, of the filler metal. The data collected from the literature are summarized in Table 4.5, in which the ratio $\rho_{M2}$ was calculated according to Equation 4.6a. To obtain the ratio $\rho_{M2}$ for Equation 4.6b, the ratio $\rho_{M2}$ for Equation 4.6a is multiplied by 1.12. The associated coefficient $V_{M2}$ is same for both Equations 4.6a and 4.6b.

Similar to the treatment to the geometric factor, the specimens are separated into two groups, namely, specimens with measured throat dimension and specimens with measured leg size. For each group, the material factor, $\rho_{M2}$, and the coefficient of variation, $V_{M2}$, are calculated. Then, all data are pooled to obtain additional values of $\rho_{M2}$ and $V_{M2}$.

Pham (1983b) tested longitudinal fillet welds on specimens of the Werner type, illustrated in Figure 4.4, while other test programs used lapped splice specimens. The Werner specimen has the advantage of eliminating both in-plane and out-of-plane eccentricity in single lapped joints.

The size effect on the longitudinal weld strength was investigated by plotting the bias coefficient $\rho_{M2}$ against the measured weld leg size in Figure 4.5, in which the leg size was determined from the measured throat size if the leg size was not reported (leg size

equal to 1.414 times measured throat size without considering face reinforcement). The figure shows no significant effect of the leg size on the bias coefficient $\rho_{M2}$.

The bias coefficient $\rho_{M2}$ may also be affected by the tensile strength of the weld metal. The ratio $\rho_{M2}$ is plotted as a function of the measured tensile strength of the weld metal in Figure 4.6. The figure shows no particular effect of the tensile strength on the bias coefficient $\rho_{M2}$.

### *4.2.4 Professional Factor, $\rho_P$, for Joints with Only One Weld Orientation*

The professional factor, $\rho_P$ , and the associated coefficient of variation, $V_P$ , for connections with a single orientation fillet weld are summarized in Table 4.6. The samples do not include the longitudinal welds because the longitudinal weld test results were used to evaluate the value of $\tau_u$ in Equation 4.7. Most (85%) specimens with single orientation fillet welds presented in Table 4.6 were with transverse welds and a few specimens with other weld orientations. Similar to the treatment of the geometric factor, $\rho_G$, and material factor, $\rho_{M2}$, the specimens were separated into two groups and then pooled to get the professional factor, $\rho_P$, and associated coefficient of variation, $V_P$ .

The professional factor for SOFW joints with transverse welds, $\rho_P$ , is plotted as a function of the measured weld size in Figure 4.7. It can be seen that the leg size has no significant effect on the professional factor, $\rho_P$. Similarly, a plot of the professional factor for transverse welds versus measured filler metal tensile strength, presented in Figure 4.8, shows no correlation between the professional factor and the tensile strength of the filler metal.

### *4.2.5 Professional Factor, $\rho_P$, for Joints with Multiple Weld Orientations*

As discussed in Section 4.1, three models are used to predict the capacity of MOFW connections with transverse and longitudinal welds. The professional factor, $\rho_P$, and the associated coefficient of variation, $V_P$, for MOFW connections, except the specimens

with out-of-plane eccentricity from Ligtenberg (1968) (see Figure 4.9), are summarized in Tables 4.7a, 4.7b, and 4.7c. All the test specimens presented in the tables combined transverse and longitudinal welds.

Figure 4.10 presents a plot of the professional factor for the test specimens presented in Table 4.7a, $\rho_P$, versus the measured tensile strength of the filler metal. The tensile strength of the filler metal has no significant effect on the professional factor, $\rho_p$. The same trend is applicable to the professional factors calculated by Equations 4.10 and Equation 4.11a and 4.11b.

### *4.2.6 Professional Factor, $\rho_p$, for Cruciform Connections*

The strengths of 12 cruciform specimens from phases 1 and 4 were predicted using Equation 4.1a. The resulting professional factor, $\rho_p$, and associated coefficient of variation, $V_p$ are presented in Table 4.8.

The professional factor, $\rho_p$, and the associated coefficient of variation, $V_p$, for cruciform specimens from phases 1 and 4 and from Pham (1983a) are summarized in Table 4.9. For specimens from Pham (1983a), the longitudinal welds of Werner specimens from Pham (1983b) were used to calculate the shear strength, $\tau_u$, in Equation 4.7 to obtain the professional factor, $\rho_p$.

## 4.3 Safety Level of Lapped Splice Connections

### *4.3.1 Connections with Single Orientation Fillet Welds*

The test programs presented in Table 4.6 were used to conduct a reliability analysis to determine the level of safety provided by the current North American design equations for design of fillet welds with a single orientation. The weld dimension measurement method is also treated as a factor for the reliability analysis. The results of this analysis and the resistance factors for various levels of safety index are presented in Table 4.10.

The results in Table 4.10 indicate that the weld measurement method has a very small effect on the safety indices. The general trend is the group of specimens with measured throat dimension yields a safety index about 3% larger than does the group of specimens with measured leg size.

The analysis results for all pooled data in Table 4.10 indicate the following observations. For CSA S16.1-01 (CSA 2001) design Equation 4.1a, the analysis indicates that a safety index of 4.5 is obtained with a resistance factor of 0.68 (0.67 is currently used in the design standard). A value of 4.0 is obtained for a resistance factor of 0.77. For the AISC design specification (AISC 2005), defined by Equation 4.1b, the analysis indicates that a safety index of 4.5 is obtained with a resistance factor of 0.76 (0.75 is currently used in the design specification). A value of 4.0 is obtained for a resistance factor of 0.86.

### *4.3.2 Connections with Fillet Welds Oriented in Multiple Directions*

A reliability analysis was performed to assess the level of safety provided by three different models to calculate the strength of welded joints combining fillet welds with transverse and longitudinal orientations. The data presented in Tables 4.7a, 4.7b and 4.7c served as the primary data for this evaluation.

The safety indices obtained based on all pooled data are presented in Table 4.11 for weld strength equations presented in both S16.1-01 (CSA 2001) and ANSI/AISC 360-05 (AISC 2005). The result for weld strength equation of S16.1-01 (CSA 2001) has indicated that for design Equation 4.9 (Model 1) and design Equation 4.11a, b (Model 3), safety indices are slightly larger than 4.5. However, for design Equation 4.10 (Model 2), the safety index is less than the traditional target value for connections of 4.5. To reach a safety index of 4.5 when the S16-01 design equation is considered, a resistance factor of 0.63 for design Equation 4.10 may be used. To reach a safety index of 4.0, a resistance factor of 0.77 for design Equation 4.9, 0.71 for design Equation 4.10, and 0.77 for design Equation 4.11a, b may be used. A similar result is obtained for weld strength equations of ANSI/AISC 360-05 (AISC 2005).

A reliability analysis conducted on the specimens with out-of-plane eccentricity from Ligtenberg (1968), as shown in Figure 4.9, is summarized in Table 4.12. The reliability analysis was conducted for only one model, namely, Equation 4.9 (Model 1). The reliability analysis based on 33 such MOFW specimens has indicated that for S16.1-01 (CSA 2001) a safety index of 4.5 is reached for a resistance factor of 0.51 and a value of 4.0 is obtained for a resistance factor of 0.58. For ANSI/AISC 360-05 (AISC 2005) a safety index of 4.5 is reached for a resistance factor of 0.57 and a value of 4.0 is obtained for a resistance factor of 0.65. The significantly lower resistance factors required for these specimens compared to the resistance factor required for the concentrically loaded test specimens illustrates the significant impact of the out-of-plane eccentricity on joint strength.

### 4.4 Safety Level of Cruciform Connections

A reliability analysis was performed for the test specimens presented in Table 4.9. The results of this analysis are presented in Table 4.13.

The reliability analysis indicates that a safety index of 4.3 is obtained with a resistance factor of 0.67 for design Equation 4.1a and a safety index of 4.3 is also obtained with a resistance factor of 0.75 for design Equation 4.1b. To achieve a safety index of 4.5, the resistance factor for Equation 4.1a needs to be decreased to 0.64 and the resistance factor for Equation 4.1b to 0.72. To reach a safety index of 4.0, a resistance factor of 0.73 is required for design Equation 4.1a and a resistance factor of 0.82 for design Equation 4.1b.

**Table 4.1** – Summary of Geometric Factor $\rho_G$ from Various Sources

| Weld Dimension Measurement Method | Source of Data | Nominal Leg Size (mm) | Sample Size n | Ratio of Measured to Nominal $\rho_G$ | Coefficient of Variation $V_G$ |
|---|---|---|---|---|---|
| Measured Throat Dimension | Bornscheuer and Feder (1966) | 5.7 | 8 | 0.957 | 0.090 |
| | | 11.3 | 6 | 0.938 | 0.048 |
| | | 17.0 | 5 | 0.921 | 0.020 |
| | Ligtenberg (1968) | 4.2 | 97 | 1.230 | 0.168 |
| | | 5.0 | 67 | 1.121 | 0.163 |
| | | 5.7 | 91 | 1.109 | 0.171 |
| | | 6.4 | 13 | 1.071 | 0.096 |
| | | 7.1 | 302 | 1.056 | 0.155 |
| | | 8.5 | 145 | 1.039 | 0.147 |
| | | 10.6 | 41 | 0.986 | 0.098 |
| | | 11.3 | 87 | 0.997 | 0.100 |
| | | 14.1 | 31 | 0.996 | 0.124 |
| | Kato and Morita (1969) | 5.0 | 8 | 1.057 | 0.065 |
| | | 7.0 | 1 | 1.041 | — |
| | | 10.0 | 3 | 1.009 | 0.021 |
| | | 12.0 | 1 | 0.953 | — |
| | | 15.0 | 6 | 1.014 | 0.005 |
| | | 20.0 | 3 | 0.96 | 0.079 |
| | | 22.0 | 1 | 0.929 | — |
| | | 30.0 | 1 | 1.000 | — |
| | | 40.0 | 2 | 0.940 | 0.09 |
| | Clark (1971) | 7.9 | 18 | 0.985 | 0.065 |
| | Pham (1981) | 5.0 | 17 | 1.072 | 0.102 |
| | | 10.0 | 6 | 1.058 | 0.051 |
| | | 16.0 | 3 | 1.030 | 0.054 |
| | All Specimens with Measured Throat Dimension | N.A. | 973 | 1.065 | 0.148 |

**Table 4.1 (cont.)**

| Weld Dimension Measurement Method | Source of Data | Nominal Leg Size | Sample Size | Ratio of Measured to Nominal | Coefficient of Variation |
|---|---|---|---|---|---|
| | | (mm) | n | $\rho_G$ | $V_G$ |
| Measured Leg Size | Butler and Kulak (1969) | 6.4 | 31 | 1.138 | 0.069 |
| | Dawe and Kulak (1972) | 6.4 | 43 | 1.158 | 0.075 |
| | Swannell (1979b) | 6.4 | 21 | 1.070 | 0.031 |
| | Pham (1983a, b) | 6.0 | 22 | 1.346 | 0.060 |
| | | 10.0 | 23 | 1.118 | 0.106 |
| | | 16.0 | 23 | 1.072 | 0.081 |
| | Miazga and Kennedy (1986) | 5.0 | 21 | 1.040 | 0.026 |
| | | 9.0 | 21 | 1.030 | 0.027 |
| | Bowman and Quinn (1994) | 6.4 | 8 | 1.182 | 0.082 |
| | | 9.5 | 4 | 1.128 | 0.040 |
| | | 12.7 | 6 | 1.087 | 0.030 |
| | Phase 1 through 4 | 6.4 | 126 | 1.026 | 0.102 |
| | | 7.9 | 48 | 1.118 | 0.061 |
| | | 12.7 | 336 | 1.078 | 0.161 |
| | All Specimens with Measured Leg Size | N.A. | 733 | 1.087 | 0.126 |
| All Sources | | N.A. | 1706 | 1.074 | 0.142 |

**Table 4.2** – Geometric Factor $\rho_G$ for Specimens from Current Test Program

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | CPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| CNY-1 | 12.7 | Front | 12.9 | 10.3 | 9.7 | 8.0 | 1.205 | 1.184 | 0.896 |
| | | Back | 11.9 | 9.9 | 9.8 | 7.6 | 1.294 | 1.278 | 0.844 |
| CNY-2 | 12.7 | Front | 11.9 | 12.7 | 10.9 | 8.7 | 1.257 | 1.255 | 0.966 |
| | | Back | 11.5 | 11.4 | 11.0 | 8.1 | 1.357 | 1.358 | 0.902 |
| CNY-3 | 12.7 | Front | 12.9 | 12.0 | 12.1 | 8.8 | 1.378 | 1.376 | 0.978 |
| | | Back | 13.5 | 10.7 | 11.6 | 8.4 | 1.383 | 1.356 | 0.934 |
| CNY-4 | 12.7 | Front | 15.0 | 11.6 | 12.3 | 9.2 | 1.339 | 1.308 | 1.023 |
| | | Back | 13.5 | 10.8 | 11.3 | 8.4 | 1.340 | 1.315 | 0.939 |
| CNY-5 | 12.7 | Front | 11.5 | 11.6 | 9.4 | 8.2 | 1.153 | 1.153 | 0.908 |
| | | Back | 12.6 | 9.1 | 9.6 | 7.4 | 1.304 | 1.251 | 0.820 |
| CNY-6 | 12.7 | Front | 13.2 | 10.7 | 11.5 | 8.3 | 1.385 | 1.363 | 0.925 |
| | | Back | 12.0 | 12.6 | 11.8 | 8.7 | 1.357 | 1.356 | 0.968 |
| CNY-7 | 12.7 | Front | 12.8 | 9.5 | 8.9 | 7.7 | 1.163 | 1.126 | 0.852 |
| | | Back | 12.1 | 9.8 | 9.4 | 7.6 | 1.236 | 1.215 | 0.847 |
| CNY-8 | 12.7 | Front | 13.5 | 10.2 | 10.4 | 8.1 | 1.280 | 1.243 | 0.905 |
| | | Back | 13.1 | 10.2 | 9.8 | 8.1 | 1.215 | 1.188 | 0.898 |
| CNY-9 | 12.7 | Front | 13.5 | 10.4 | 10.8 | 8.2 | 1.312 | 1.279 | 0.917 |
| | | Back | 11.9 | 11.7 | 9.9 | 8.3 | 1.189 | 1.189 | 0.928 |
| CNY-10 | 12.7 | Front | 11.9 | 11.6 | 9.8 | 8.3 | 1.182 | 1.182 | 0.923 |
| | | Back | 11.1 | 9.6 | 9.4 | 7.3 | 1.290 | 1.280 | 0.812 |
| CNY-11 | 12.7 | Front | 12.3 | 11.8 | 10.8 | 8.5 | 1.273 | 1.272 | 0.945 |
| | | Back | 11.9 | 12.2 | 10.8 | 8.5 | 1.269 | 1.269 | 0.948 |
| CNY-12 | 12.7 | Front | 11.8 | 11.9 | 10.9 | 8.4 | 1.302 | 1.302 | 0.932 |
| | | Back | 11.1 | 12.5 | 10.3 | 8.3 | 1.244 | 1.237 | 0.922 |
| All Specimens | | | Mean of Ratios | | | | 1.280 | 1.264 | 0.914 |
| | | | Coefficient of Variation, $V$ | | | | 0.055 | 0.055 | 0.055 |

**Table 4.3** – Summary of Geometric Factor $\rho_G$ from Phases 1 through 4

| Source of Data | Nominal Leg Size | Sample Size † | Ratio $\alpha_1$ | | Ratio $\alpha_2$ | | Ratio $\rho_G$ | |
|---|---|---|---|---|---|---|---|---|
| | (mm) | n | Mean $\alpha_1$ | $V_1$ | Mean $\alpha_2$ | $V_2$ | Mean $\rho_G$ | $V_G$ |
| Ng *et al.* (2002) | 6.4 | 126 | 1.165 | 0.070 | 1.145 | 0.077 | 1.026 | 0.102 |
| | 12.7 | 78 | 1.108 | 0.076 | 1.076 | 0.077 | 0.954 | 0.073 |
| Deng *et al.* (2003) | 12.7 | 54 | 1.049 | 0.085 | 1.043 | 0.086 | 0.836 | 0.053 |
| Callele *et al.* (2005) | 7.9 | 48 | 1.102 | 0.061 | 1.091 | 0.065 | 1.118 | 0.061 |
| | 12.7 | 180 | 1.106 | 0.085 | 1.090 | 0.088 | 0.981 | 0.082 |
| Current Test Program | 12.7 | 24 | 1.280 | 0.055 | 1.264 | 0.056 | 0.914 | 0.055 |
| All Specimens from Phase 1 through 4 | N.A. | 510 | 1.119 | 0.088 | 1.105 | 0.090 | 0.983 | 0.108 |

† A weld segment measured is treated as a sample.

**Table 4.4** – Summary of Material Factor $\rho_{M1}$

| Source of Data | Sample Size | Nominal Tensile Strength (MPa) | Mean Tensile Strength (MPa) | Ratio of Measured to Nominal | Coefficient of Variation | Data Set |
|---|---|---|---|---|---|---|
| | n | $X_u$ | $\sigma_u$ | $\rho_{M1}$ | $V_{M1}$ | |
| Miazga and Kennedy (1986) | 3 | 480 | 537.7 | 1.120 | 0.014 | 1 |
| Gagnon and Kennedy (1987) | 10 | 480 | 579.9 | 1.208 | 0.035 | 2 |
| Swannell and Skewes (1979) | 2 | 410 | 538.8 | 1.314 | 0.020 | 3 |
| Fisher et al. (1978) | 127 | 414 | 455.1 | 1.100 | 0.038 | 4 |
| | 138 | 483 | 516.4 | 1.070 | 0.035 | 5 |
| | 136 | 552 | 606.1 | 1.099 | 0.049 | 6 |
| | 16 | 621 | 690.9 | 1.113 | 0.043 | 7 |
| | 72 | 758 | 806.0 | 1.063 | 0.040 | 8 |
| | 128 | 483 | 588.8 | 1.220 | 0.056 | 9 |
| | 40 | 483 | 598.5 | 1.240 | 0.113 | 10 |
| Pham (1981) | 3 | 480 | 500 | 1.042 | 0.044 | 11 |
| Mansell and Yadav (1982) | 6 | 410 | 558 | 1.361 | 0.027 | 12 |
| Bowman and Quinn (1994) | 3 | 483 | 475.8 | 0.986 | 0.029 | 13 |
| Callele *et al.* (2005)† | 32 | 480 | 552.3 | 1.151 | 0.084 | 14 |
| All Sources | 716 | N.A. | N.A. | 1.127 | 0.080 | 15 |

† Including all weld metal tension coupon tests from phases 1 through 4.

**Table 4.5** – Summary of Material Factor $\rho_{M2}$ per Equation 4.6a

| Weld Dimension Measurement Method | Source of Data | | Sample Size | Ratio of Measured to Nominal | Coefficient of Variation |
|---|---|---|---|---|---|
| | | | n | $\rho_{M2}$ | $V_{M2}$ |
| Measured Throat Dimension | Ligtenberg (1968) | England (St.37 steel) | 18 | 1.077 | 0.096 |
| | | Japan (St.37 steel) | 18 | 1.103 | 0.152 |
| | | USA (St.37 steel) | 18 | 1.234 | 0.125 |
| | | France (St.37 steel) | 18 | 1.087 | 0.124 |
| | | Germany (St.37 steel) | 18 | 1.087 | 0.085 |
| | | Belgium (St.37steel) | 18 | 1.108 | 0.121 |
| | | Netherlands (St.37 steel) | 17 | 1.210 | 0.077 |
| | | Canada (St.37 steel) | 18 | 1.236 | 0.129 |
| | | Sweden (St.37 steel) | 18 | 1.149 | 0.145 |
| | | Yugoslavia (St.37 steel) | 18 | 1.195 | 0.091 |
| | | Netherlands (St.52 steel) | 10 | 1.186 | 0.093 |
| | | Germany (St.52 steel) | 10 | 1.238 | 0.117 |
| | | Italy (St.52 Steel) | 10 | 1.230 | 0.060 |
| | | Sweden (St.52 steel) | 14 | 1.306 | 0.138 |
| | Kato and Morita (1969) | | 11 | 1.116 | 0.068 |
| | All Specimens with Measured Throat Dimension | | 234 | 1.165 | 0.112 |
| Measured Leg Size | Swannell and Skewes (1979b) | | 7 | 1.045 | 0.041 |
| | Pham (1983b) | | 33 | 1.022 | 0.159 |
| | Miazga and Kennedy (1986) | | 6 | 1.141 | 0.081 |
| | Bowman and Quinn (1994) | | 6 | 1.526 | 0.135 |
| | Deng *et al.* (2003) | | 9 | 1.344 | 0.113 |
| | Callele *et al* (2005) | | 9 | 1.187 | 0.086 |
| | All Specimens with Measured Leg Size | | 70 | 1.140 | 0.180 |
| All Sources | | | 304 | 1.159 | 0.130 |

**Table 4.6** – Summary of Professional Factor $\rho_P$ for SOFW Joints

| Weld Dimension Measurement Method | Source of Data | | Orientation of Weld Segments | Sample Size | Ratio of Measured to Predicted | Coefficient of Variation |
|---|---|---|---|---|---|---|
| | | | | n | $\rho_P$ | $V_P$ |
| Measured Throat Dimension | Ligtenberg (1968) | England (St.37 steel) | 90° | 9 | 1.044 | 0.115 |
| | | Japan (St.37 steel) | 90° | 9 | 1.100 | 0.092 |
| | | USA (St.37 steel) | 90° | 9 | 0.991 | 0.129 |
| | | France (St.37 steel) | 90° | 9 | 1.047 | 0.074 |
| | | Germany (St.37 steel) | 90° | 9 | 1.132 | 0.137 |
| | | Belgium (St.37steel) | 90° | 9 | 1.128 | 0.123 |
| | | Netherlands (St.37 steel) | 90° | 9 | 1.043 | 0.093 |
| | | Canada (St.37 steel) | 90° | 9 | 1.156 | 0.090 |
| | | Sweden (St.37 steel) | 90° | 9 | 1.066 | 0.145 |
| | | Yugoslavia (St.37 steel) | 90° | 18 | 0.954 | 0.142 |
| | | Netherlands (St.52 steel) | 90° | 5 | 0.916 | 0.129 |
| | | Germany (St.52 steel) | 90° | 5 | 1.154 | 0.112 |
| | | Italy (St.52 Steel) | 90° | 5 | 0.873 | 0.060 |
| | | Sweden (St.52 steel) | 90° | 7 | 1.009 | 0.087 |
| | Bornscheuer and Feder (1966) | | 90° | 8 | 1.197 | 0.120 |
| | Kato and Morita (1969) | | 90° | 9 | 0.933 | 0.104 |
| | All Specimens with Measured Throat Dimension | | N.A. | 138 | 1.046 | 0.138 |

**Table 4.6 (cont.)**

| Weld Dimension Measurement Method | Source of Data | Orientation of Weld Segments | Sample Size | Ratio of Measured to Predicted | Coefficient of Variation |
|---|---|---|---|---|---|
| | | | n | $\rho_P$ | $V_P$ |
| Measured Leg Size | Butler and Kulak (1969) | 30° | 6 | 1.225 | 0.002 |
| | | 60° | 6 | 0.845 | 0.036 |
| | | 90° | 6 | 0.914 | 0.061 |
| | Clark (1971) | 30° | 2 | 1.352 | 0.054 |
| | | 60° | 2 | 1.067 | 0.233 |
| | | 90° | 4 | 1.139 | 0.034 |
| | Miazga and Kennedy (1986) | 15° | 6 | 0.953 | 0.051 |
| | | 30° | 6 | 1.079 | 0.056 |
| | | 45° | 6 | 0.990 | 0.129 |
| | | 60° | 6 | 1.105 | 0.112 |
| | | 75° | 6 | 0.996 | 0.018 |
| | | 90° | 6 | 0.954 | 0.056 |
| | Bowman and Quinn (1994) | 90° | 6 | 0.956 | 0.030 |
| | Ng *et al.* (2002)† | 90° | 86 | 1.169 | 0.157 |
| | Deng *et al.* (2003)† | 45° | 8 | 1.403 | 0.088 |
| | All Specimens with Measured Leg Sizes | N.A. | 162 | 1.119 | 0.168 |
| All Sources | | N.A. | 300 | 1.085 | 0.159 |

† Data were directly from literature.

**Table 4.7a** – Summary of Professional Factor $\rho_p$ for MOFW Joints for Equation 4.9

| Source of Data | | Sample Size | Ratio of Measured to Predicted | Coefficient of Variation |
|---|---|---|---|---|
| | | n | $\rho_p$ | $V_p$ |
| Ligtenberg (1968) | England (St.37 steel) | 16 | 1.085 | 0.095 |
| | Japan (St.37 steel) | 17 | 1.053 | 0.048 |
| | USA (St.37 steel) | 18 | 1.054 | 0.090 |
| | France (St.37 steel) | 18 | 1.091 | 0.106 |
| | Germany (St.37 steel) | 16 | 1.040 | 0.098 |
| | Belgium (St.37steel) | 16 | 1.136 | 0.107 |
| | Netherlands (St.37 steel) | 17 | 0.962 | 0.071 |
| | Canada (St.37 steel) | 15 | 1.121 | 0.111 |
| | Sweden (St.37 steel) | 18 | 1.036 | 0.118 |
| | Yugoslavia (St.37 steel) | 18 | 1.011 | 0.110 |
| | Netherlands (St.52 steel) | 13 | 1.029 | 0.090 |
| | Germany (St.52 steel) | 13 | 1.132 | 0.055 |
| | Italy (St.52 Steel) | 13 | 1.025 | 0.067 |
| | Sweden (St.52 steel) | 14 | 1.011 | 0.061 |
| Bornscheuer and Feder (1966) | | 5 | 0.913 | 0.042 |
| Kato and Morita (1969) | | 3 | 1.090 | 0.089 |
| Callele *et al.* (2005)† | | 20 | 0.848 | 0.075 |
| All Sources | | 262 | 1.033 | 0.114 |

† Only test program for which the throat area is calculated from measured leg dimensions. All others used the measured throat dimension.

**Table 4.7b** – Summary of Professional Factor $\rho_P$ for MOFW Joints for Equation 4.10

| Source of Data | | Sample Size | Ratio of Measured to Predicted | Coefficient of Variation |
|---|---|---|---|---|
| | | n | $\rho_P$ | $V_P$ |
| Ligtenberg (1968) | England (St.37 steel) | 16 | 0.992 | 0.101 |
| | Japan (St.37 steel) | 17 | 0.969 | 0.045 |
| | USA (St.37 steel) | 18 | 0.967 | 0.086 |
| | France (St.37 steel) | 18 | 1.001 | 0.103 |
| | Germany (St.37 steel) | 16 | 0.940 | 0.103 |
| | Belgium (St.37steel) | 16 | 1.025 | 0.108 |
| | Netherlands (St.37 steel) | 17 | 0.875 | 0.080 |
| | Canada (St.37 steel) | 15 | 1.024 | 0.102 |
| | Sweden (St.37 steel) | 18 | 0.946 | 0.114 |
| | Yugoslavia (St.37 steel) | 18 | 0.922 | 0.120 |
| | Netherlands (St.52 steel) | 13 | 0.943 | 0.085 |
| | Germany (St.52 steel) | 13 | 1.035 | 0.048 |
| | Italy (St.52 Steel) | 13 | 0.935 | 0.066 |
| | Sweden (St.52 steel) | 14 | 0.948 | 0.067 |
| Bornscheuer and Feder (1966) | | 5 | 0.785 | 0.033 |
| Kato and Morita (1969) | | 3 | 1.024 | 0.117 |
| Callele *et al.* (2005)† | | 20 | 0.779 | 0.073 |
| All Sources | | 262 | 0.944 | 0.114 |

† Only test program for which the throat area is calculated from measured leg dimensions. All others used the measured throat dimension.

**Table 4.7c** – Summary of Professional Factor $\rho_P$ for MOFW Joints for Equation 4.11a and b

| Source of Data | | Sample Size | Ratio of Measured to Predicted | Coefficient of Variation |
|---|---|---|---|---|
| | | n | $\rho_P$ | $V_P$ |
| Ligtenberg (1968) | England (St.37 steel) | 16 | 1.082 | 0.100 |
| | Japan (St.37 steel) | 17 | 1.050 | 0.057 |
| | USA (St.37 steel) | 18 | 1.052 | 0.091 |
| | France (St.37 steel) | 18 | 1.088 | 0.104 |
| | Germany (St.37 steel) | 16 | 1.026 | 0.111 |
| | Belgium (St.37steel) | 16 | 1.117 | 0.115 |
| | Netherlands (St.37 steel) | 17 | 0.952 | 0.076 |
| | Canada (St.37 steel) | 15 | 1.117 | 0.111 |
| | Sweden (St.37 steel) | 18 | 1.031 | 0.120 |
| | Yugoslavia (St.37 steel) | 18 | 1.003 | 0.117 |
| | Netherlands (St.52 steel) | 13 | 1.028 | 0.090 |
| | Germany (St.52 steel) | 13 | 1.129 | 0.051 |
| | Italy (St.52 Steel) | 13 | 1.023 | 0.068 |
| | Sweden (St.52 steel) | 14 | 1.011 | 0.061 |
| Bornscheuer and Feder (1966) | | 5 | 0.913 | 0.042 |
| Kato and Morita (1969) | | 3 | 1.090 | 0.089 |
| Callele *et al.* (2005)† | | 20 | 0.848 | 0.075 |
| All Sources | | 262 | 1.028 | 0.115 |

† Only test program for which the throat area is calculated from measured leg dimensions. All others used the measured throat dimension.

**Table 4.8** – Professional Factor $\rho_P$ for Cruciform Specimens from Phases 1 and 4

| Specimen | Phase | Weld Metal Spec. | Nominal Leg Size (mm) | $P_{ST} / A_{throat}$ (MPa) | $\tau_u$ (MPa) | Ratio $\rho_P$ | Mean $\rho_P$ | $V_P$ |
|---|---|---|---|---|---|---|---|---|
| C1-1 | 1 | E70T-4 | 6.4 | 1067 | 496 | 1.433 | 1.204 | 0.154 |
| C1-2 | | | | 1028 | | 1.381 | | |
| C1-3 | | | | 943 | | 1.267 | | |
| C2-1 | | E70T7-K2 | | 997 | 600 | 1.107 | | |
| C2-2 | | | | 954 | | 1.059 | | |
| C2-3 | | | | 877 | | 0.974 | | |
| CNY-7 | 4 | E70T-7 | 12.7 | 539 | 453 | 0.794 | 0.817 | 0.082 |
| CNY-8 | | | | 609 | | 0.897 | | |
| CNY-10 | | | | 615 | | 0.906 | | |
| CNY-6 | | E71T8-K6 | | 572 | 500 | 0.762 | | |
| CNY-11 | | | | 577 | | 0.769 | | |
| CNY-12 | | | | 578 | | 0.771 | | |

**Table 4.9** – Summary of Professional Factor $\rho_P$ for Cruciform Connections

| Source of Data | | Sample Size | Ratio of Measured to Predicted | Coefficient of Variation |
|---|---|---|---|---|
| | | n | $\rho_P$ | $V_P$ |
| Ng *et al.* (2002) | FCAW, 6.4 mm | 6 | 1.204 | 0.154 |
| Current Test | FCAW, 12.7 mm | 6 | 0.817 | 0.082 |
| Pham (1983a) | FCAW, 6 mm | 6 | 1.206 | 0.042 |
| | FCAW, 10 mm | 6 | 0.888 | 0.072 |
| | FCAW, 16 mm | 6 | 0.906 | 0.099 |
| | SAW, 6 mm | 6 | 1.091 | 0.033 |
| | SAW, 10 mm | 6 | 1.251 | 0.030 |
| | SAW, 16 mm | 6 | 0.981 | 0.054 |
| All specimens | | 48 | 1.043 | 0.170 |

**Table 4.10** – Summary of Safety Indices for SOFW Joints

| | | Equation 4.1a CSA S16.1-01 | | | Equation 4.1b AISC 2005 | | |
|---|---|---|---|---|---|---|---|
| Weld Dimension Measurement Method | | Measured Throat Dimension | Measured Leg Size | All Sources | Measured Throat Dimension | Measured Leg Size | All Sources |
| $\rho_G$ | | 1.065 | 1.087 | 1.074 | 1.065 | 1.087 | 1.074 |
| $V_G$ | | 0.148 | 0.126 | 0.142 | 0.148 | 0.126 | 0.142 |
| $\rho_{M1}$ | | 1.127 | 1.127 | 1.127 | 1.127 | 1.127 | 1.127 |
| $V_{M1}$ | | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 |
| $\rho_{M2}$ | | 1.165 | 1.140 | 1.159 | 1.301 | 1.273 | 1.294 |
| $V_{M2}$ | | 0.112 | 0.180 | 0.130 | 0.112 | 0.180 | 0.130 |
| $\rho_P$ | | 1.046 | 1.119 | 1.085 | 1.046 | 1.119 | 1.085 |
| $V_P$ | | 0.138 | 0.168 | 0.159 | 0.138 | 0.168 | 0.159 |
| $\rho_R$ | | 1.463 | 1.563 | 1.522 | 1.633 | 1.745 | 1.699 |
| $V_R$ | | 0.245 | 0.288 | 0.262 | 0.245 | 0.288 | 0.262 |
| $\beta$ | $\phi_w = 0.67$ | 4.59 | 4.42 | 4.57 | — | — | — |
| | $\phi = 0.75$ | — | — | — | 4.51 | 4.41 | 4.55 |
| $\phi_w$ | $\beta = 4.5$ | 0.68 | 0.66 | 0.68 | — | — | — |
| $\phi$ | | — | — | — | 0.76 | 0.73 | 0.76 |
| $\phi_w$ | $\beta = 4.0$ | 0.77 | 0.75 | 0.77 | — | — | — |
| $\phi$ | | — | — | — | 0.86 | 0.83 | 0.86 |

**Table 4.11** – Summary of Safety Indices for MOFW Joints

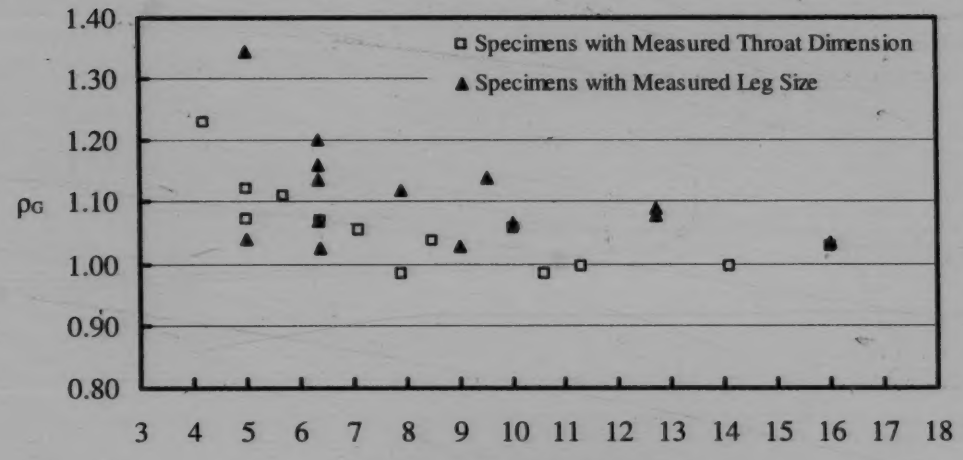
| Model | | Model 1 Equation 4.9 | | Model 2 Equation 4.10 | | Model 3 Equations 4.11a and b | |
|---|---|---|---|---|---|---|---|
| Design Code | | S16.1-01 | AISC 2005 | S16.1-01 | AISC 2005 | S16.1-01 | AISC 2005 |
| $\rho_G$ | | 1.074 | 1.074 | 1.074 | 1.074 | 1.074 | 1.074 |
| $V_G$ | | 0.142 | 0.142 | 0.142 | 0.142 | 0.142 | 0.142 |
| $\rho_{M1}$ | | 1.127 | 1.127 | 1.127 | 1.127 | 1.127 | 1.127 |
| $V_{M1}$ | | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 |
| $\rho_{M2}$ | | 1.159 | 1.294 | 1.159 | 1.294 | 1.159 | 1.294 |
| $V_{M2}$ | | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 |
| $\rho_P$ | | 1.033 | 1.033 | 0.944 | 0.944 | 1.028 | 1.028 |
| $V_P$ | | 0.114 | 0.114 | 0.114 | 0.114 | 0.115 | 0.115 |
| $\rho_R$ | | 1.449 | 1.618 | 1.324 | 1.479 | 1.442 | 1.610 |
| $V_R$ | | 0.238 | 0.238 | 0.238 | 0.238 | 0.238 | 0.238 |
| $\beta$ | $\phi_w = 0.67$ | 4.63 | — | 4.23 | — | 4.60 | — |
| | $\phi = 0.75$ | — | 4.61 | — | 4.22 | — | 4.60 |
| $\phi_w$ | $\beta = 4.5$ | 0.69 | — | 0.63 | — | 0.69 | — |
| $\phi$ | | — | 0.77 | — | 0.70 | — | 0.77 |
| $\phi_w$ | $\beta = 4.0$ | 0.77 | — | 0.71 | — | 0.77 | — |
| $\phi$ | | — | 0.86 | — | 0.79 | — | 0.86 |

**Table 4.12** – Summary of Safety Indices for MOFW Specimens with Out-of-plane Eccentricity from Ligtenberg (1968)

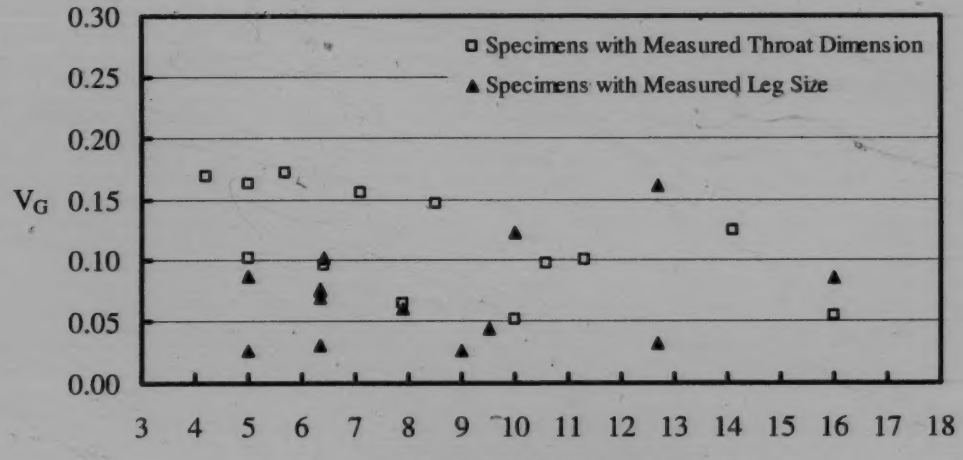
| | | Model 1 Equation 4.9 | |
|---|---|---|---|
| Design Code | | S16.1-01 | AISC 2005 |
| $\rho_G$ | | 1.074 | 1.074 |
| $V_G$ | | 0.142 | 0.142 |
| $\rho_{M1}$ | | 1.127 | 1.127 |
| $V_{M1}$ | | 0.080 | 0.080 |
| $\rho_{M2}$ | | 1.159 | 1.294 |
| $V_{M2}$ | | 0.130 | 0.130 |
| $\rho_P$ | | 0.878 | 0.878 |
| $V_P$ | | 0.211 | 0.211 |
| $\rho_R$ | | 1.232 | 1.377 |
| $V_R$ | | 0.297 | 0.302 |
| $\beta$ | $\phi_w = 0.67$ | 3.45 | — |
| | $\phi = 0.75$ | — | 3.44 |
| $\phi_w$ | $\beta = 4.5$ | 0.51 | — |
| $\phi$ | | — | 0.57 |
| $\phi_w$ | $\beta = 4.0$ | 0.58 | — |
| $\phi$ | | — | 0.65 |

**Table 4.13** – Summary of Safety Indices for Cruciform Joints

| | | CSA S16.1-01 Equation 4.1a | AISC 2005 Equation 4.1b |
|---|---|---|---|
| $\rho_G$ | | 1.074 | 1.074 |
| $V_G$ | | 0.142 | 0.142 |
| $\rho_{M1}$ | | 1.127 | 1.127 |
| $V_{M1}$ | | 0.080 | 0.080 |
| $\rho_{M2}$ | | 1.159 | 1.294 |
| $V_{M2}$ | | 0.130 | 0.130 |
| $\rho_P$ | | 1.043 | 1.043 |
| $V_P$ | | 0.170 | 0.170 |
| $\rho_R$ | | 1.463 | 1.634 |
| $V_R$ | | 0.269 | 0.269 |
| $\beta$ | $\phi_w = 0.67$ | 4.34 | — |
| | $\phi = 0.75$ | — | 4.33 |
| $\phi_w$ | $\beta = 4.5$ | 0.64 | — |
| $\phi$ | | — | 0.72 |
| $\phi_w$ | $\beta = 4.0$ | 0.73 | — |
| $\phi$ | | — | 0.81 |




a) Variation of $\rho_G$ with Weld Size




b) Variation of $V_G$ with Weld Size

**Figure 4.1** – Variation of $\rho_G$ and $V_G$ with Weld Size

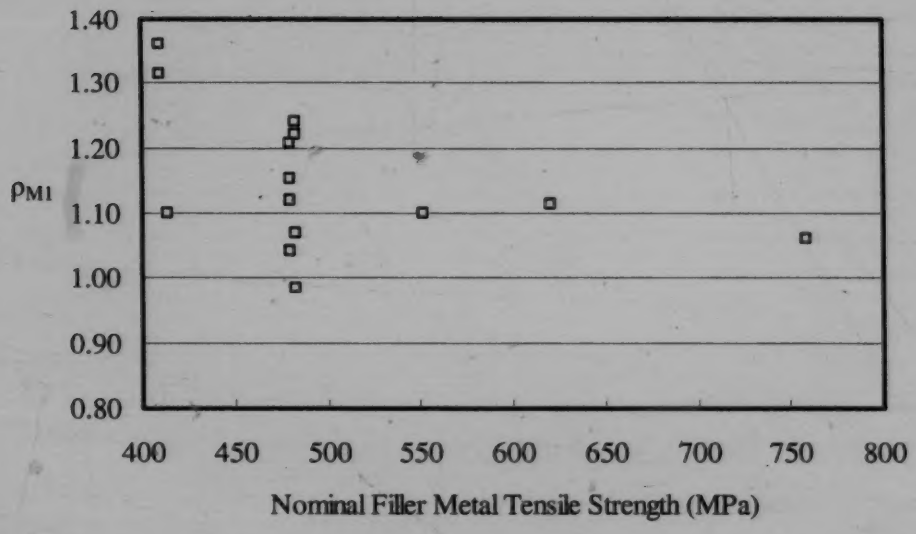



**Figure 4.2** – Value of $\rho_{M1}$ as a Function of the Nominal Tensile Strength from Various Sources

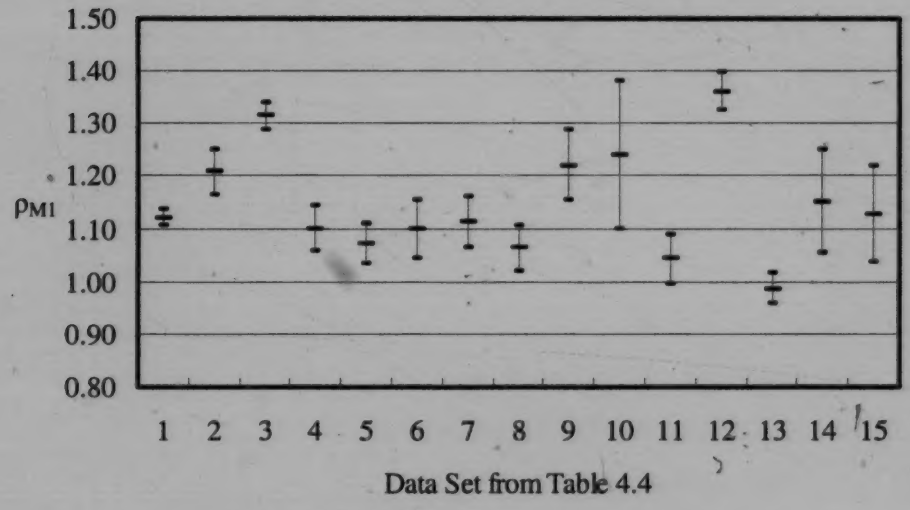



**Figure 4.3** – Variation of $\rho_{M1}$ in Various Data Sets

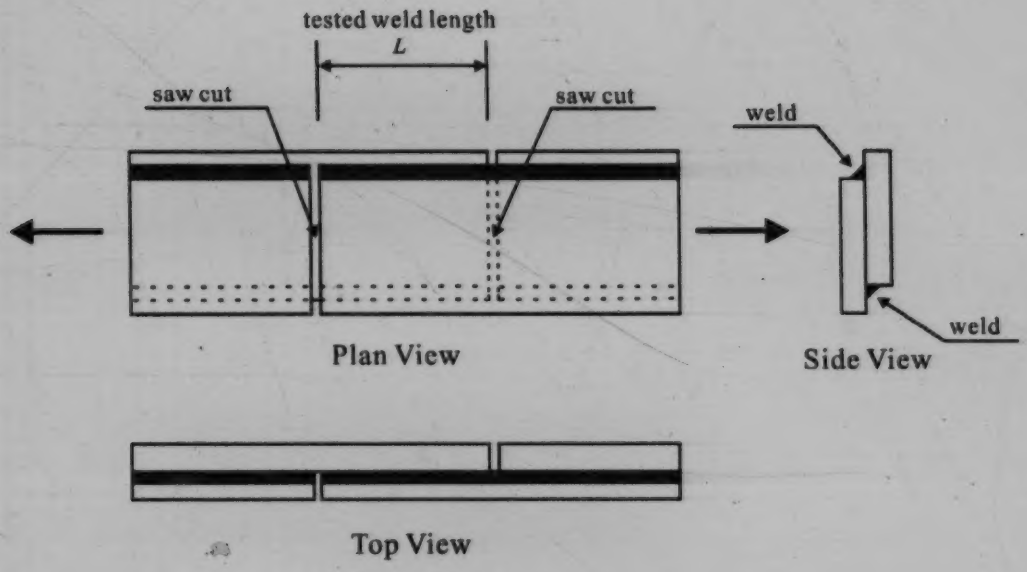



**Figure 4.4** – Werner Specimen

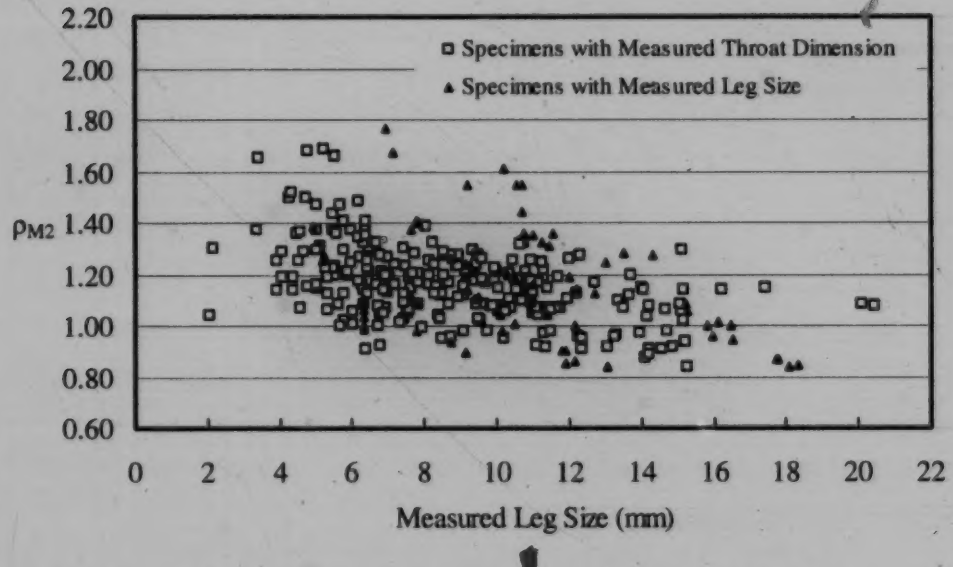



**Figure 4.5** – Bias Coefficient $\rho_{M2}$ as a Function of Weld Size

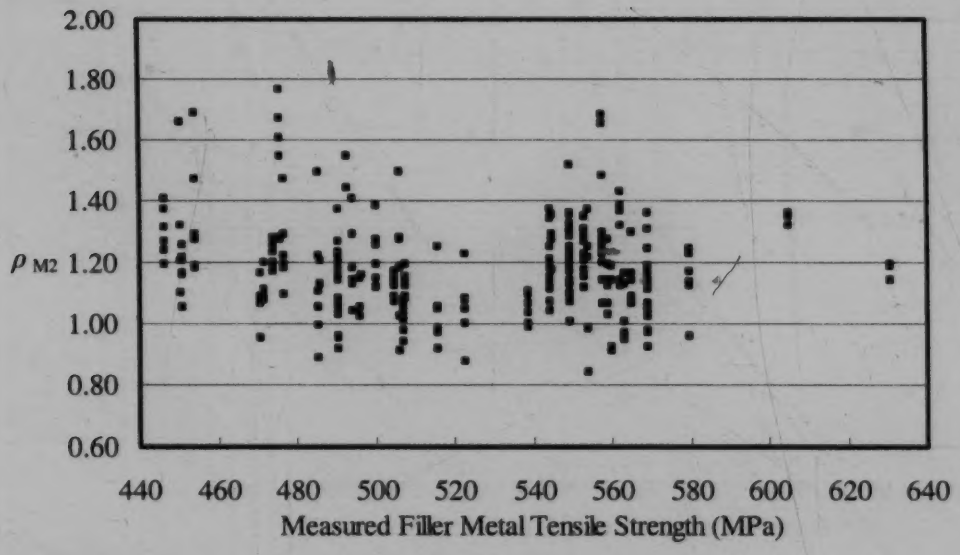



**Figure 4.6** – Effect of Tensile Strength on the Bias Coefficient $\rho_{M2}$ for All Test Specimens in Table 4.5

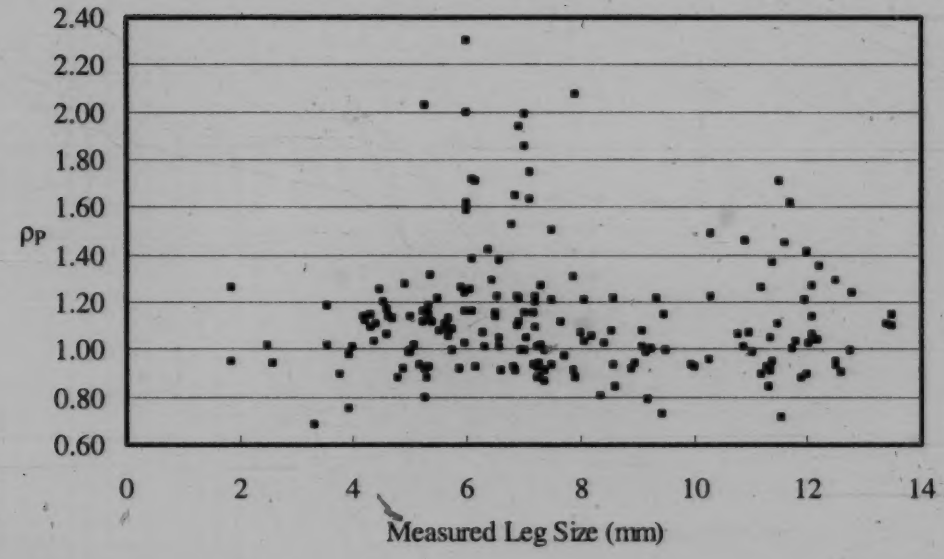



**Figure 4.7** – Professional Factor, $\rho_P$, for Transverse Weld versus Measured Weld Size

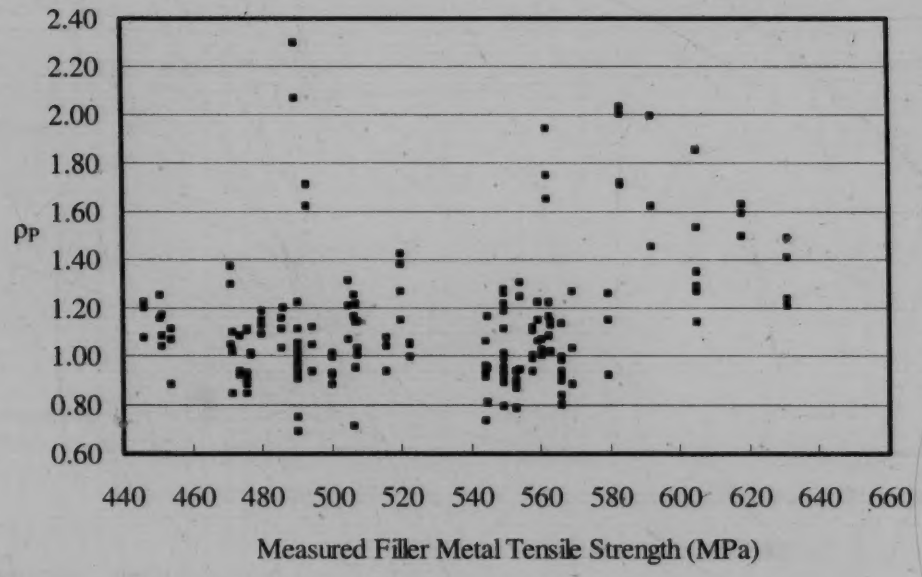



**Figure 4.8** – Professional Factor, $\rho_P$, for Transverse Weld versus Measured Filler Metal Tensile Strength

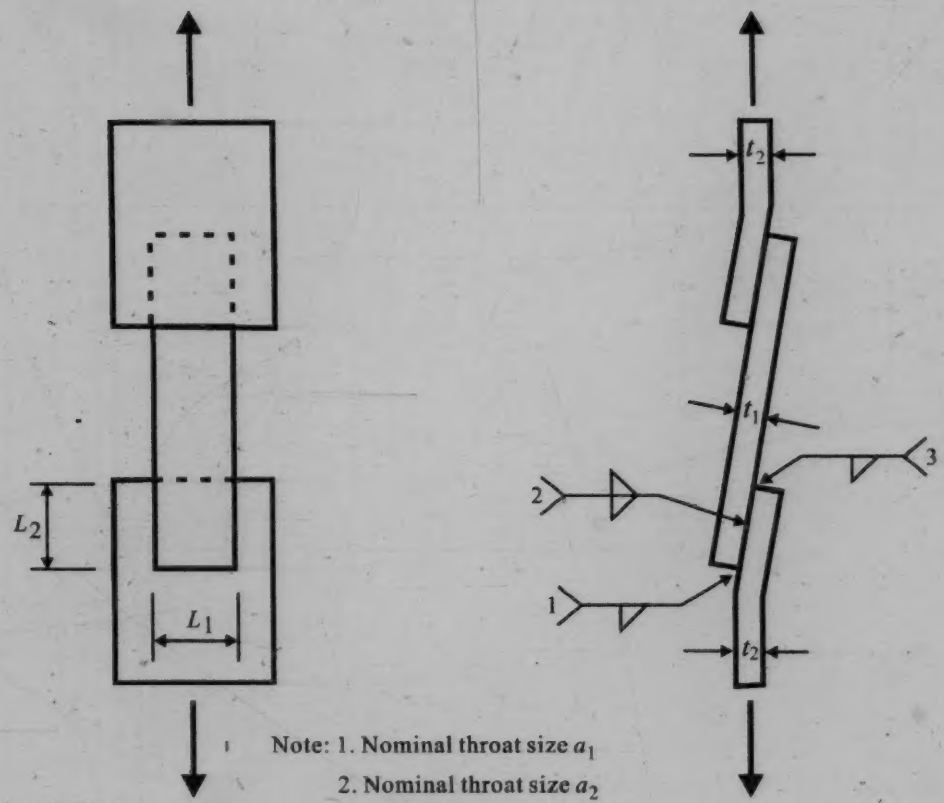



**Figure 4.9** – MOFW Specimen with Out-of-plane Eccentricity from Ligtenberg (1968)

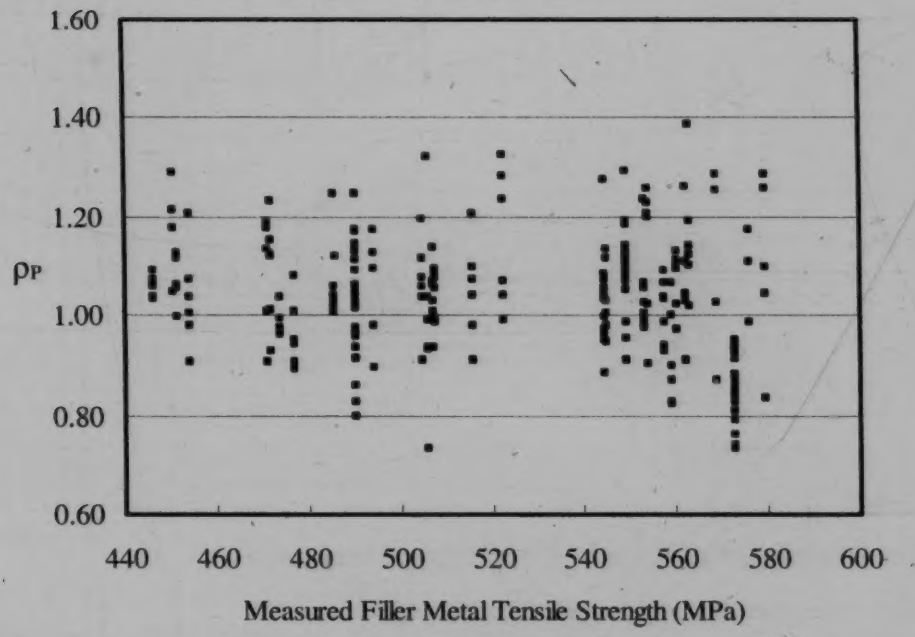



**Figure 4.10** – Professional Factor, $\rho_p$, for Combined Transverse and Longitudinal Welds versus Measured Filler Metal Tensile Strength

# CHAPTER 5

# SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 5. 1 Summary

An extensive research program on the strength and ductility of fillet welds in concentrically loaded joints has been conducted at the University of Alberta. Although the test program included five different filler metal classifications, this represents only a small fraction of the filler metals used in industry. The primary objective of this investigation was to augment the database of test results from the University of Alberta to include test results from other sources to increase the variety of filler metal classifications included in the database. This database of test results was then used to conduct a reliability analysis of the current North American design equation for design of fillet welds in concentrically loaded joints.

A review of the literature showed that most experimental programs have used double lap joints, with limited tests on cruciform connections. Therefore, a series of 12 cruciform specimens were tested. All specimens consisted of 12.7 mm welds prepared using two FCAW filler metals, namely, E70T-7 filler metal (AWS, 1995) and E71T8-K6 filler metal, with a toughness requirement of 20J at -29°C (AWS, 1998). The steel plates conformed to the requirements of ASTM A572 Grade 50 and were designed to remain elastic throughout the tests. Six cruciform specimens were tested at -50°C. The specimens were concentrically loaded under displacement control.

The data pool collected from various sources includes 1706 measurements of fillet weld size, 716 all-weld-metal coupon test specimens, 304 test specimens with longitudinal fillet welds, 300 test specimens with single orientation fillet welds (SOFW) other than longitudinal welds, 262 test specimens with multiple orientation fillet welds (MOFW) and 48 cruciform test specimens. The specimens were welded with filler metals from at least 10 different classifications. The test specimens included in the database were prepared using SMAW, FCAW or SAW welding processes.

## 5. 2 Conclusions

The following conclusions can be drawn from the test program on cruciform specimens:

1. A comparison of the strength of cruciform joints and lapped joints with transverse welds of the same classification indicated that 12.7 mm welds in cruciform joints reached only 81% of the strength of transverse fillet welds in lapped joints for E70T-7 electrodes and 70% for E71T8-K6 electrodes. A similar comparison in phase 1 of the research program indicated that 6.4 mm welds made with E70T-4 electrodes were not affected by the joint configuration, whereas 6.4 mm fillet welds from E70T7-K2 electrodes showed that cruciform joints had only 87% of the strength of lapped joints with transverse welds.

2. A comparison of weld ductility for E70T-7 electrodes on plates that remained elastic during testing indicated an average strain at ultimate load of cruciform specimens of 100% of that of lapped specimens and an average strain at fracture of cruciform specimens of 70% of that of lapped specimens. Ng *et al.* (2002) indicated that the mean ductility of lapped joints is about 3.8 times that of cruciform joints. It is noted that in phase 1 the plates yielded before fracture of the welds.

3. The importance of second order effects from main plate misalignment on the behaviour of cruciform test specimens was investigated. For the test specimens included in the database of test results (all from phase 4 of this research program), the fabrication imperfections were not considered to have had a significant effect on the behaviour of the specimens.

The following conclusions are drawn from an analysis of the database of test results:

4. The bias coefficient for the geometric factor, $\rho_G$, is larger for small weld sizes than for larger weld sizes. The coefficient of variation for the geometric factor, $V_G$, was found to be smaller for large welds than for small welds. This reflects the difficulty of producing small size welds. The bias coefficient, $\rho_G$, and the

coefficient of variation, $V_G$, for the pooled data are 1.074 and 0.142, respectively. The geometric factor, $\rho_G$, and the coefficient of variation, $V_G$, from phases 1 through 4, in which the strict tolerances were set on the weld size, were 0.983 and 0.108, respectively.

5. For the data available, there seems to be no correlation between the ratio of measured weld metal tensile strength to the nominal tensile strength, $\rho_{M1}$, and the nominal strength. The bias coefficient for the material strength factor, $\rho_{M1}$, from phases 1 through 4 fell within one standard deviation of the mean from all the pooled data. The values of $\rho_{M1}$ and $V_{M1}$ were therefore obtained from the whole data pool. The bias coefficient, $\rho_{M1}$, and the coefficient of variation, $V_{M1}$, are taken as 1.127 and 0.08, respectively.

6. The material factor, $\rho_{M2}$, is defined as the ratio of measured weld shear strength, which is obtained from longitudinal test specimens, to 0.67 (for CSA S16–01) or 0.60 (for ANSI/AISC 360-05) times the measured tensile strength. The material factor, $\rho_{M2}$, therefore represents a normalized capacity of the longitudinal test specimens. The size effect on the longitudinal weld strength was investigated by examining the bias coefficient $\rho_{M2}$ against the measured weld leg size. This investigation indicated no significant effect of the leg size on the material factor, $\rho_{M2}$. The effect of the measured tensile strength of the electrode on the longitudinal weld strength was also investigated. No significant effect of the tensile strength on the bias coefficient, $\rho_{M2}$, was observed. The bias coefficient, $\rho_{M2}$, and the coefficient of variation, $V_{M2}$, are taken as 1.159 and 0.130 for CSA S16.1-01 and 1.294 and 0.130 for ANSI/AISC 360-05, respectively.

7. About 85% of the specimens with single orientation fillet welds had transverse welds. The professional factor, $\rho_P$, for joints with transverse welds only was analyzed as the function of the measured leg size. No correlation between the professional factor and the measured weld size was observed. Similarly, no

correlation was found between the professional factor and the measured tensile strength of the filler metal.

8. The professional factor for MOFW joints with combined transverse and longitudinal welds for the design equation proposed by Callele *et al.* (2005) was analyzed as the function of the measured tensile strength of the filler metal. It was observed that the tensile strength of the filler metal has no significant effect on the professional factor.

9. The effect of the fillet weld characteristic dimension, namely, measurement of leg dimension or measurement of throat dimension, on the bias coefficient was investigated. Overall, the weld size has only a small effect on the values of $\rho_G$, $\rho_{M2}$ and $\rho_P$.

10. The test data from Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al.* (2005) and the current test program, which included nominal leg sizes of 6.4 mm, 7.9 mm and 12.7 mm, show that the throat dimension measured before testing is about 10% larger than the throat dimension calculated from the measured leg sizes.

The following conclusions are drawn from the reliability analysis:

11. A reliability analysis of SOFW joints from various sources has indicated that a safety index of 4.5 is obtained with a resistance factor of 0.68 for the CSA S16.1-01 design equation and a resistance factor of 0.76 for the ANSI/AISC 360-05 design equation. A safety index of 4.0 is obtained for a resistance factor of 0.77 with the weld strength equation presented in CSA S16.1-01 and a resistance factor of 0.86 with the weld strength equation presented in ANSI/AISC 360-05.

12. A reliability analysis of MOFW joints from four different sources has indicated that the weld strength equation proposed by Callele *et al.* (2005) yields safety indices of 4.5 and 4.0 for resistance factors of 0.69 and 0.77, respectively. The

addition of the full strength of all the welds in the MOFW joint, as deduced from CSA S16.1-01, results in safety indices of 4.5 and 4.0 for resistance factors of 0.63 and 0.71, respectively. The equation adopted by AISC (2005) for joints with transverse and longitudinal welds results in safety indices of 4.5 and 4.0 for resistance factors of 0.69 and 0.77, respectively. The results have confirmed that the design equation proposed by Callele *et al.* (2005) and that used in AISC (2005), adopted from the work of Manuel and Kulak (2000) provide a sufficient level of safety.

13. A reliability analysis conducted on 33 MOFW specimens with out-of-plane eccentricity from Ligtenberg (1968) was performed for the design equation proposed by Callele *et al.* (2005) only. The analysis indicated that safety indices of 4.5 and 4.0 are obtained with resistance factors of 0.50 and 0.57, respectively. The weld strength design equation proposed by Callele *et al.* is not suitable for MOFW joints with out-of-plane eccentricity.

14. A reliability analysis of cruciform joints was performed for the CSA S16.1-01 design equation (Equation 4.1a) and the ANSI/AISC 360-05 design equation (Equation 4.1b). The analysis indicated that for the CSA S16.1-01 design equation, safety indices of 4.5 and 4.0 are obtained with resistance factors of 0.64 and 0.72, respectively. For the ANSI/AISC 360-05 design equation, safety indices of 4.5 and 4.0 are obtained with resistance factors of 0.71 and 0.81, respectively.

### 5. 3 Recommendations for Future Research

Although the research on concentrically loaded fillet welded joints presented in this report has helped expand our knowledge regarding fillet weld behaviour, other issues still need to be addressed.

1. A comparison between the strength of lapped and cruciform joints has indicated that both weld size and weld metal toughness have an effect on the strength reduction of cruciform specimens. In phases 1 and 4, only two leg sizes and two FCAW electrodes were used for cruciform specimens. Other leg sizes and a wider

variety of welding electrodes with and without a toughness requirement are recommended to investigate their effects on the strength of cruciform specimens.

2. The size of the root notch present in cruciform joints may be a significant factor on the strength and ductility of these joints since the root notch represents a notch oriented perpendicular to the applied stress field. Further testing is recommended to investigate the effect of root notch size on the strength and ductility of cruciform joints.

3. The specimens tested at low temperature in phases 3 and 4 fractured in the plates rather than in the weld. Therefore, the low temperature effect on the behaviour of fillet welds remains inconclusive. Further testing is recommended to investigate the effect of low temperature on fillet welds.

4. Canadian practice (CSA, 2003) for longitudinal welds requires a weld return to terminate the weld. The length of the return must be at lease twice the nominal size of the weld. The weld returns for longitudinal welds are essentially short transverse welds. It is possible that the presence of the short transverse welds will prevent the longitudinal welds from reaching their full capacity due to the difference in ductilities. Further testing is recommended to investigate the effect of weld returns on the strength of longitudinal welds.

5. Based on the above recommendations, new specimens were designed and their drawings and general requirements for fabrication are presented in Appendix F.

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# APPENDIX A

# ALL-WELD-METAL TENSION COUPON TESTS

# APPENDIX A

## ALL-WELD-METAL TENSION COUPON TESTS

This appendix contains information for the three all-weld-metal tension coupon tests on E71T8-K6 filler metal. Test results for the E70T-7 filler metal used in this investigation were reported in Appendix C of Callele *et al.* (2005) (coupons 103-1, 2, 3) and repeated here for completeness.

The stresses shown in the following figures are calculated as engineering stress, i.e., the applied load divided by the initial area. Table A1 gives the initial areas and the post-fracture areas. The initial cross-sectional areas were calculated from nine measurements of the diameter in the test region of the coupons. The post-fracture areas were calculated from six diameter measurements taken on both of the two fracture areas from each coupon. All of the diameter measurements were made with a calliper. A summary of the key stress and strain values is provided in Table 3.2.

**Table A1 –** Coupon Cross-Sectional Areas

| Electrode | Coupon | Cross-Sectional Area | | |
|---|---|---|---|---|
| | | Initial ($mm^2$) | Post-Fracture ($mm^2$) | Reduction (%) |
| E70T–7 | 103–1 | 126 | 109 | 13.7 |
| | 103–2 | 127 | 111 | 12.4 |
| | 103–3 | 128 | 103 | 19.1 |
| E71T8–K6 | 203–1 | 127 | 40 | 68.5 |
| | 203–2 | 127 | 42 | 66.9 |
| | 203–3 | 127 | 41 | 67.7 |

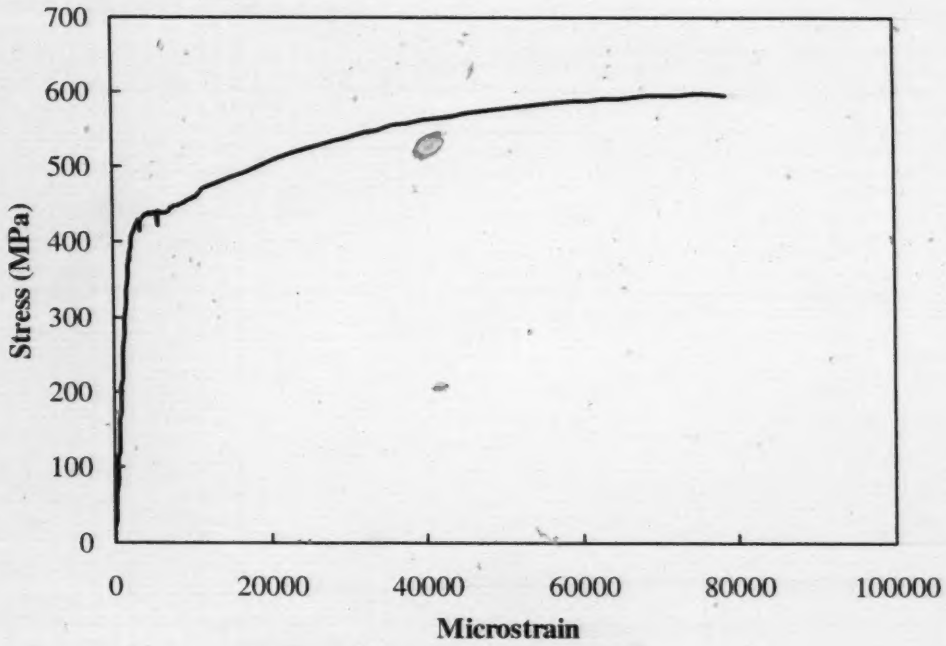



**Figure A1** – Test Coupon 103–1

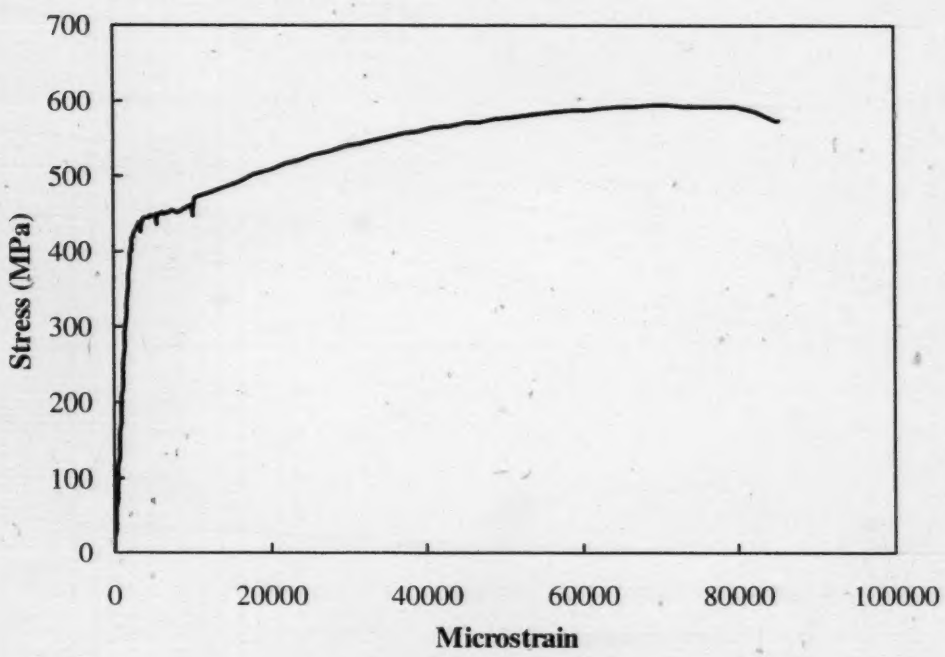



**Figure A2** – Test Coupon 103–2

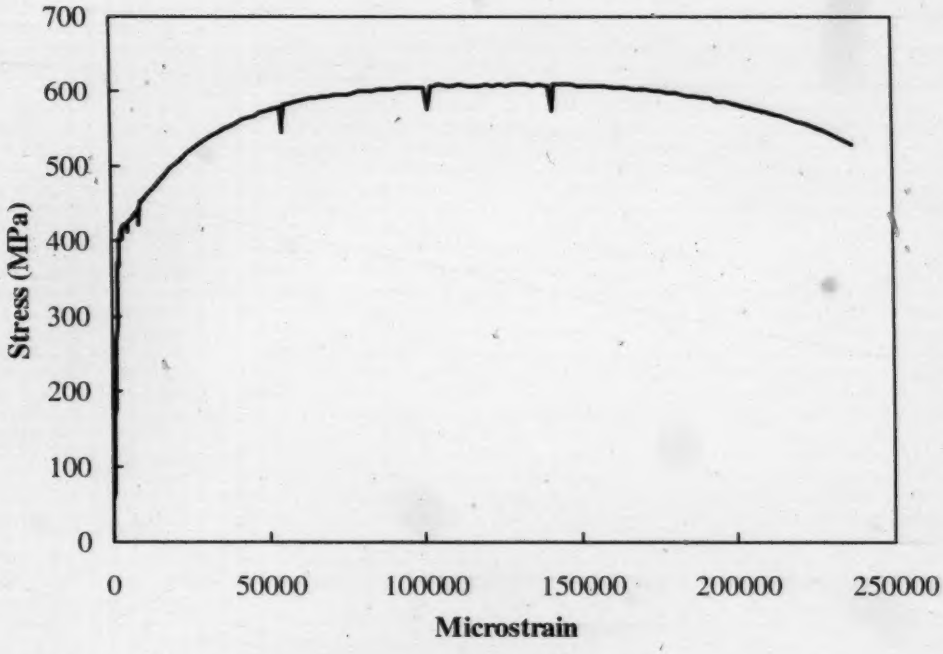



**Figure A3** – Test Coupon 103–3

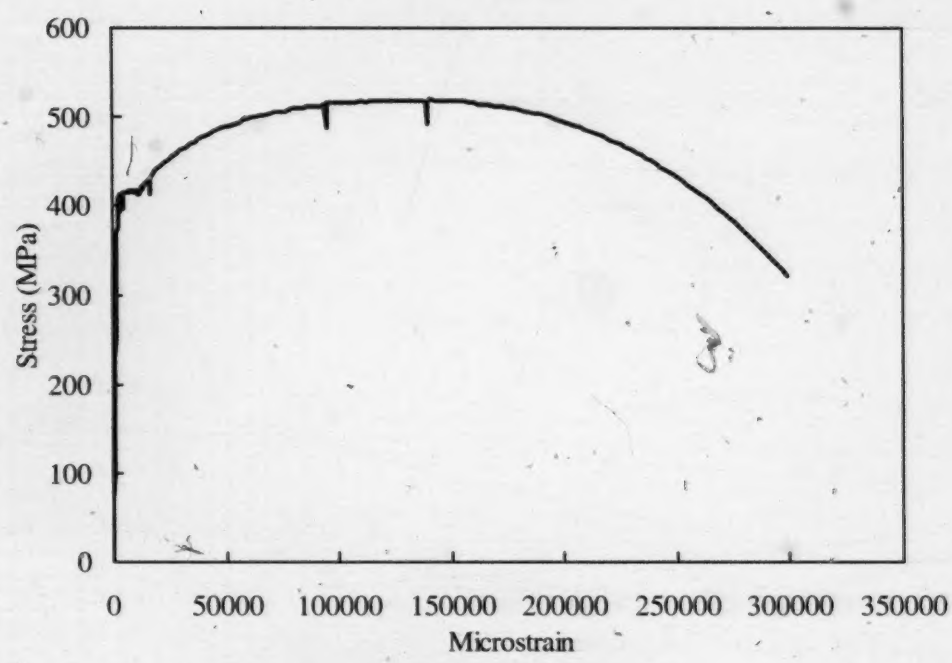



**Figure A4** – Test Coupon 203–1

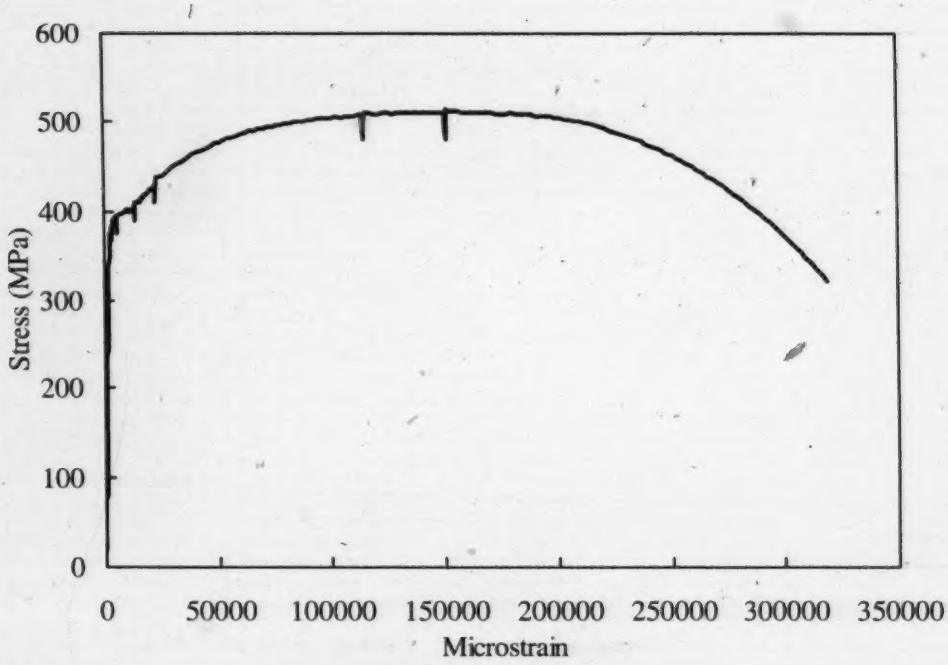



**Figure A5** – Test Coupon 203–2

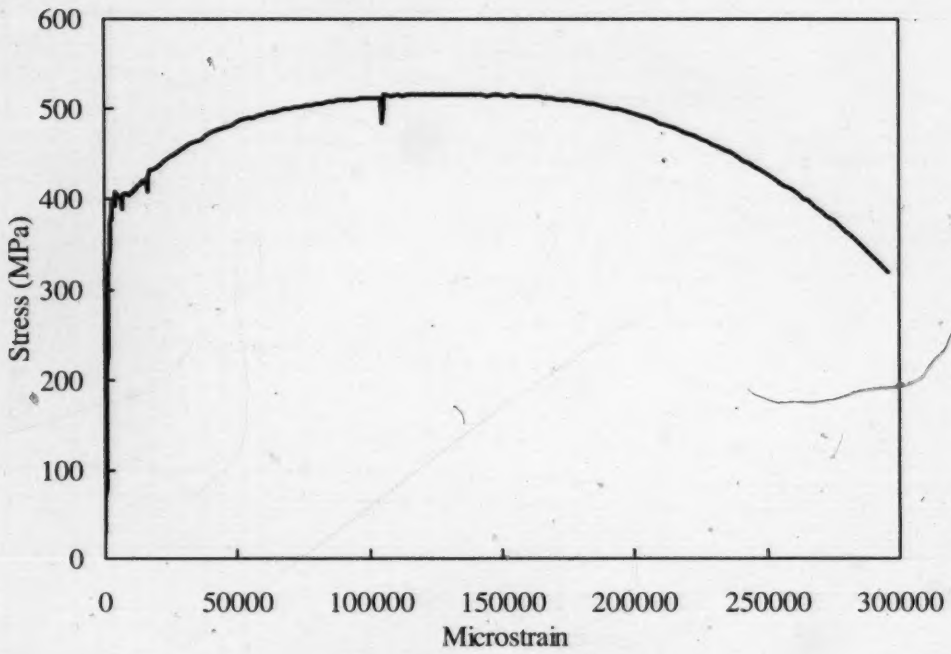



**Figure A6** – Test Coupon 203–3

# APPENDIX B

# FILLET WELD SPECIMEN MEASUREMENTS

# APPENDIX B

## MEASUREMENTS OF FILLET WELD SPECIMENS

Refer to Section 3.4 and Figure 3.2 for definitions and measurement method.

**Table B1** – Weld Measurements for Specimen CNY–1 (E70T-7, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 12.8 | 10.4 | 10.0 | 72.4 | 11.3 | 9.3 | 9.2 | 72.4 |
| 2 | 14.0 | 10.8 | 9.7 | 72.4 | 12.1 | 9.4 | 9.4 | 72.4 |
| 3 | 14.0 | 11.4 | 10.5 | 72.4 | 12.1 | 9.8 | 9.8 | 72.4 |
| 4 | 12.0 | 10.7 | 9.8 | | 12.2 | 9.8 | 10.3 | |
| 5 | 12.1 | 10.3 | 9.8 | | 12.0 | 10.2 | 10.5 | |
| 6 | 12.5 | 9.8 | 9.4 | | 12.0 | 10.5 | 10.5 | |
| 7 | 12.6 | 9.6 | 9.2 | | 11.6 | 10.2 | 9.8 | |
| 8 | 13.0 | 9.5 | 9.4 | | 11.4 | 9.7 | 9.2 | |
| Mean | 12.9 | 10.3 | 9.7 | 72.4 | 11.8 | 9.9 | 9.8 | 72.4 |
| Gauge Length (mm) | LVDT1 = 14.4 | | | | LVDT3 = 15.7 | | | |
| | LVDT2 = 14.4 | | | | LVDT4 = 13.6 | | | |

**Table B2** – Weld Measurements for Specimen CNY–2 (E71T8-K6, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 11.0 | 12.8 | 9.8 | 76.3 | 11.8 | 11.5 | 11.1 | 76.3 |
| 2 | 11.4 | 12.2 | 10.5 | 76.3 | 11.2 | 11.2 | 11.0 | 76.3 |
| 3 | 11.5 | 12.3 | 11.0 | 76.3 | 11.5 | 11.6 | 11.0 | 76.3 |
| 4 | 10.9 | 13.0 | 11.0 | | 11.3 | 11.8 | 11.0 | |
| 5 | 12.6 | 12.7 | 11.3 | | 11.0 | 12.3 | 11.3 | |
| 6 | 13.2 | 12.7 | 11.1 | | 11.1 | 11.7 | 10.8 | |
| 7 | 12.6 | 12.7 | 11.3 | | 11.1 | 11.4 | 10.5 | |
| 8 | 12.0 | 13.0 | 11.0 | | 11.8 | 11.8 | 11.3 | |
| Mean | 11.9 | 12.7 | 10.9 | 76.3 | 11.3 | 11.7 | 11.0 | 76.3 |
| Gauge Length (mm) | LVDT1 = 16.1 | | | | LVDT3 = 14.9 | | | |
| | LVDT2 = 12.3 | | | | LVDT4 = 14.0 | | | |

**Table B3** – Weld Measurements for Specimen CNY–3 (E71T8-K6, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 12.6 | 11.3 | 12.4 | 76.3 | 14.5 | 10.4 | 12.2 | 76.3 |
| 2 | 12.0 | 12.1 | 11.9 | 76.4 | 13.3 | 10.3 | 11.9 | 76.3 |
| 3 | 12.9 | 12.3 | 11.3 | 76.3 | 12.6 | 10.1 | 11.3 | 76.3 |
| 4 | 12.5 | 12.2 | 12.5 | | 12.8 | 11.6 | 11.3 | |
| 5 | 13.0 | 11.4 | 12.2 | | 13.3 | 11.1 | 11.4 | |
| 6 | 13.6 | 11.4 | 12.4 | | 14.1 | 10.8 | 11.7 | |
| 7 | 13.5 | 12.9 | 12.5 | | 13.7 | 10.9 | 11.6 | |
| 8 | 13.1 | 12.1 | 11.7 | | 13.7 | 10.6 | 11.4 | |
| Mean | 12.9 | 12.0 | 12.1 | 76.3 | 13.5 | 10.7 | 11.6 | 76.3 |
| Gauge Length (mm) | LVDT1 = 16.8 | | | | LVDT3 = 17.3 | | | |
| | LVDT2 = 13.8 | | | | LVDT4 = 15.8 | | | |

**Table B4** – Weld Measurements for Specimen CNY–4 (E71T8-K6, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 14.0 | 12.0 | 12.2 | 76.3 | 13.5 | 10.9 | 11.3 | 76.3 |
| 2 | 13.9 | 11.9 | 12.4 | 76.3 | 13.2 | 10.3 | 11.1 | 76.3 |
| 3 | 14.8 | 12.0 | 12.5 | 76.3 | 13.3 | 10.5 | 10.6 | 76.3 |
| 4 | 15.6 | 12.0 | 12.2 | | 13.3 | 11.0 | 11.3 | |
| 5 | 14.0 | 10.6 | 12.2 | | 13.5 | 10.8 | 11.1 | |
| 6 | 15.9 | 11.2 | 12.1 | | 13.1 | 10.5 | 11.4 | |
| 7 | 17.3 | 11.9 | 12.4 | | 14.0 | 11.1 | 11.7 | |
| 8 | 14.3 | 11.5 | 12.2 | | 14.1 | 11.3 | 11.6 | |
| Mean | 15.0 | 11.6 | 12.3 | 76.3 | 13.5 | 10.8 | 11.3 | 76.3 |
| Gauge Length (mm) | LVDT1 = 19.6 | | | | LVDT3 = 17.1 | | | |
| | LVDT2 = 14.9 | | | | LVDT4 = 15.6 | | | |

**Table B5** – Weld Measurements for Specimen CNY–5 (E70T-7, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 12.5 | 10.8 | 9.2 | 72.5 | 12.5 | 8.4 | 9.7 | 72.4 |
| 2 | 12.2 | 11.1 | 9.4 | 72.5 | 12.3 | 9.0 | 9.7 | 72.5 |
| 3 | 11.1 | 11.2 | 9.5 | 72.4 | 12.8 | 9.2 | 9.5 | 72.5 |
| 4 | 11.3 | 11.3 | 9.5 | | 12.8 | 8.6 | 9.4 | |
| 5 | 11.3 | 11.9 | 9.5 | | 12.7 | 8.9 | 9.7 | |
| 6 | 11.3 | 12.2 | 9.5 | | 12.9 | 9.7 | 9.7 | |
| 7 | 11.2 | 12.4 | 9.4 | | 12.3 | 9.1 | 9.8 | |
| 8 | 10.8 | 12.0 | 9.0 | | 12.9 | 9.7 | 9.5 | |
| Mean | 11.5 | 11.6 | 9.4 | 72.5 | 12.6 | 9.1 | 9.6 | 72.4 |
| Gauge Length (mm) | LVDT1 = 13.6 | | | | LVDT3 = 16.2 | | | |
| | LVDT2 = 13.6 | | | | LVDT4 = 14.8 | | | |

**Table B6** – Weld Measurements for Specimen CNY–6 (E71T8-K6, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 13.7 | 11.0 | 11.6 | 76.3 | 12.1 | 12.6 | 12.5 | 76.3 |
| 2 | 13.6 | 11.0 | 12.2 | 76.3 | 11.9 | 13.1 | 12.5 | 76.3 |
| 3 | 13.6 | 11.2 | 11.0 | 76.3 | 11.8 | 13.4 | 11.9 | 76.3 |
| 4 | 12.5 | 11.1 | 11.4 | | 12.8 | 12.2 | 11.9 | |
| 5 | 12.5 | 9.7 | 11.3 | | 11.6 | 12.2 | 11.1 | |
| 6 | 12.4 | 10.1 | 11.9 | | 11.4 | 12.1 | 11.7 | |
| 7 | 13.5 | 10.6 | 11.4 | | 12.1 | 13.0 | 11.3 | |
| 8 | 13.5 | 10.9 | 11.3 | | 12.2 | 12.4 | 11.6 | |
| Mean | 13.2 | 10.7 | 11.5 | 76.3 | 12.0 | 12.6 | 11.8 | 76.3 |
| Gauge Length (mm) | LVDT1 = 16.1 | | | | LVDT3 = 17.6 | | | |
| | LVDT2 = 15.6 | | | | LVDT4 = 15.8 | | | |

**Table B7** – Weld Measurements for Specimen CNY–7 (E70T-7, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 12.8 | 9.8 | 9.0 | 72.5 | 13.2 | 9.3 | 9.2 | 72.4 |
| 2 | 11.8 | 9.6 | 9.2 | 72.5 | 12.5 | 9.7 | 9.7 | 72.4 |
| 3 | 12.1 | 9.8 | 8.3 | 72.4 | 12.1 | 10.1 | 9.4 | 72.4 |
| 4 | 12.5 | 10.0 | 8.7 | | 11.9 | 10.0 | 9.5 | |
| 5 | 12.6 | 9.3 | 8.9 | | 11.4 | 9.9 | 9.2 | |
| 6 | 13.5 | 9.7 | 8.7 | | 11.6 | 9.2 | 9.5 | |
| 7 | 13.7 | 9.2 | 9.4 | | 12.2 | 10.0 | 9.2 | |
| 8 | 13.5 | 9.1 | 9.4 | | 12.2 | 9.8 | 9.5 | |
| Mean | 12.8 | 9.5 | 8.9 | 72.5 | 12.1 | 9.8 | 9.4 | 72.4 |
| Gauge Length (mm) | LVDT1 = 15.4 | | | | LVDT3 = 14.7 | | | |
| | LVDT2 = 13.0 | | | | LVDT4 = 13.8 | | | |

**Table B8** – Weld Measurements for Specimen CNY–8 (E70T-7, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 13.9 | 10.4 | 11.0 | 72.4 | 12.9 | 9.7 | 9.8 | 72.5 |
| 2 | 14.4 | 10.4 | 10.3 | 72.5 | 13.2 | 9.8 | 9.8 | 72.4 |
| 3 | 13.5 | 10.4 | 10.3 | 72.4 | 13.0 | 10.9 | 10.2 | 72.4 |
| 4 | 13.6 | 9.6 | 10.5 | | 13.6 | 11.2 | 9.8 | |
| 5 | 13.3 | 10.7 | 10.6 | | 13.3 | 10.4 | 10.2 | |
| 6 | 13.5 | 10.1 | 10.3 | | 12.9 | 10.2 | 9.8 | |
| 7 | 13.2 | 9.9 | 10.0 | | 13.0 | 9.9 | 9.2 | |
| 8 | 12.6 | 9.7 | 9.8 | | 12.8 | 9.8 | 9.2 | |
| Mean | 13.5 | 10.1 | 10.4 | 72.4 | 13.1 | 10.2 | 9.8 | 72.4 |
| Gauge Length (mm) | LVDT1 = 14.1 | | | | LVDT3 = 16.2 | | | |
| | LVDT2 = 14.5 | | | | LVDT4 = 15.4 | | | |

**Table B9** – Weld Measurements for Specimen CNY–9 (E70T-7, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45o Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45o Meas. (mm) | Weld Length (mm) |
| 1 | 12.8 | 9.9 | 10.6 | 72.5 | 12.7 | 11.5 | 9.7 | 72.4 |
| 2 | 12.7 | 10.0 | 10.8 | 72.4 | 13.5 | 11.9 | 10.5 | 72.4 |
| 3 | 13.5 | 10.5 | 10.6 | 72.4 | 11.3 | 12.4 | 11.0 | 72.4 |
| 4 | 14.0 | 10.5 | 11.0 | | 12.7 | 12.4 | 10.3 | |
| 5 | 14.2 | 10.0 | 11.0 | | 12.0 | 11.8 | 9.8 | |
| 6 | 14.0 | 10.7 | 10.8 | | 11.3 | 11.5 | 9.7 | |
| 7 | 13.3 | 10.8 | 10.6 | | 11.5 | 10.8 | 9.4 | |
| 8 | 13.2 | 10.7 | 10.6 | | 10.3 | 11.0 | 9.2 | |
| Mean | 13.5 | 10.4 | 10.8 | 72.4 | 11.9 | 11.7 | 9.9 | 72.4 |
| Gauge Length (mm) | LVDT1 = 16.2 | | | | LVDT3 = 14.8 | | | |
| | LVDT2 = 15.7 | | | | LVDT4 = 15.0 | | | |

**Table B10** – Weld Measurements for Specimen CNY–10 (E70T-7, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 11.1 | 12.0 | 9.2 | 72.4 | 11.8 | 9.4 | 9.4 | 72.3 |
| 2 | 12.0 | 12.1 | 9.4 | 72.4 | 11.9 | 9.6 | 9.4 | 72.3 |
| 3 | 12.2 | 11.4 | 9.4 | 72.4 | 11.0 | 9.5 | 9.2 | 72.3 |
| 4 | 11.9 | 11.5 | 9.7 | | 11.2 | 9.7 | 9.5 | |
| 5 | 11.2 | 11.4 | 9.7 | | 11.4 | 10.0 | 9.4 | |
| 6 | 11.8 | 11.3 | 10.3 | | 11.5 | 9.6 | 9.4 | |
| 7 | 12.4 | 11.6 | 11.0 | | 11.1 | 9.7 | 9.4 | |
| 8 | 12.7 | 11.2 | 10.0 | | 11.8 | 9.6 | 9.5 | |
| Mean | 11.9 | 11.6 | 9.8 | 72.4 | 11.5 | 9.6 | 9.4 | 72.3 |
| Gauge Length (mm) | LVDT1 = 14.2 | | | | LVDT3 = 15.0 | | | |
| | LVDT2 = 12.0 | | | | LVDT4 = 13.7 | | | |

**Table B11** – Weld Measurements for Specimen CNY–11 (E71T8-K6, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 12.9 | 12.4 | 11.0 | 76.3 | 10.8 | 12.0 | 11.0 | 76.3 |
| 2 | 12.7 | 12.0 | 10.8 | 76.3 | 11.1 | 12.2 | 10.5 | 76.3 |
| 3 | 11.9 | 11.7 | 10.6 | 76.3 | 11.5 | 12.2 | 11.4 | 76.3 |
| 4 | 12.4 | 11.2 | 10.6 | | 11.6 | 12.0 | 10.8 | |
| 5 | 11.6 | 12.0 | 11.0 | | 10.9 | 12.3 | 11.0 | |
| 6 | 12.6 | 11.3 | 10.8 | | 12.2 | 12.1 | 10.3 | |
| 7 | 11.5 | 11.5 | 10.6 | | 14.0 | 12.2 | 11.4 | |
| 8 | 12.5 | 12.2 | 10.8 | | 13.1 | 12.3 | 10.3 | |
| Mean | 12.3 | 11.8 | 10.8 | 76.3 | 11.9 | 12.2 | 10.8 | 76.3 |
| Gauge Length (mm) | LVDT1 = 16.6 | | | | LVDT3 = 17.0 | | | |
| | LVDT2 = 14.7 | | | | LVDT4 = 12.8 | | | |

**Table B12** – Weld Measurements for Specimen CNY–12 (E71T8-K6, 12.7 mm)

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | CPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 11.7 | 11.1 | 10.8 | 76.3 | 12.9 | 12.0 | 10.3 | 76.3 |
| 2 | 10.7 | 11.4 | 11.3 | 76.3 | 12.2 | 12.9 | 10.2 | 76.3 |
| 3 | 11.2 | 11.9 | 10.6 | 76.3 | 10.7 | 13.1 | 9.5 | 76.3 |
| 4 | 10.4 | 12.2 | 10.8 | | 10.3 | 12.7 | 10.3 | |
| 5 | 12.8 | 12.6 | 11.0 | | 10.4 | 12.3 | 10.2 | |
| 6 | 12.8 | 11.3 | 11.1 | | 10.0 | 12.6 | 9.8 | |
| 7 | 12.3 | 12.1 | 10.8 | | 10.5 | 12.1 | 10.8 | |
| 8 | 12.8 | 12.2 | 10.6 | | 11.5 | 12.2 | 11.0 | |
| Mean | 11.8 | 11.9 | 10.9 | 76.3 | 11.1 | 12.5 | 10.3 | 76.3 |
| Gauge Length (mm) | LVDT1 = 14.8 | | | | LVDT3 = 15.9 | | | |
| | LVDT2 = 14.2 | | | | LVDT4 = 14.2 | | | |

# APPENDIX C

# SPECIMEN RESPONSE CURVES (ROOM TEMPERATURE TESTS)

## APPENDIX C

## SPECIMEN RESPONSE CURVES (ROOM TEMPERATURE TESTS)

### C.1 Response Curves Measured by LVDTs

The response curves from specimens tested at room temperature are presented in this appendix and those for specimens tested at -50°C are presented in Appendix D. The response curves measured by LVDTs are presented in Figures C1 to C6 in the format illustrated generically in Figure C0, explained as follows:

1. The vertical axis presents the value of $P/A_{throat}$, which is defined in Chapter 3.
2. The horizontal axis presents the weld strain expressed in microstrain and calculated as $\Delta/d^* \times 10^6$. The definition of $\Delta/d^*$ is also presented in Chapter 3.
3. Stress versus strain curves are presented for each of the four LVDTs used to monitor the fillet welds.
4. The inserted illustration shows the location and number of LVDTs used in the tests.

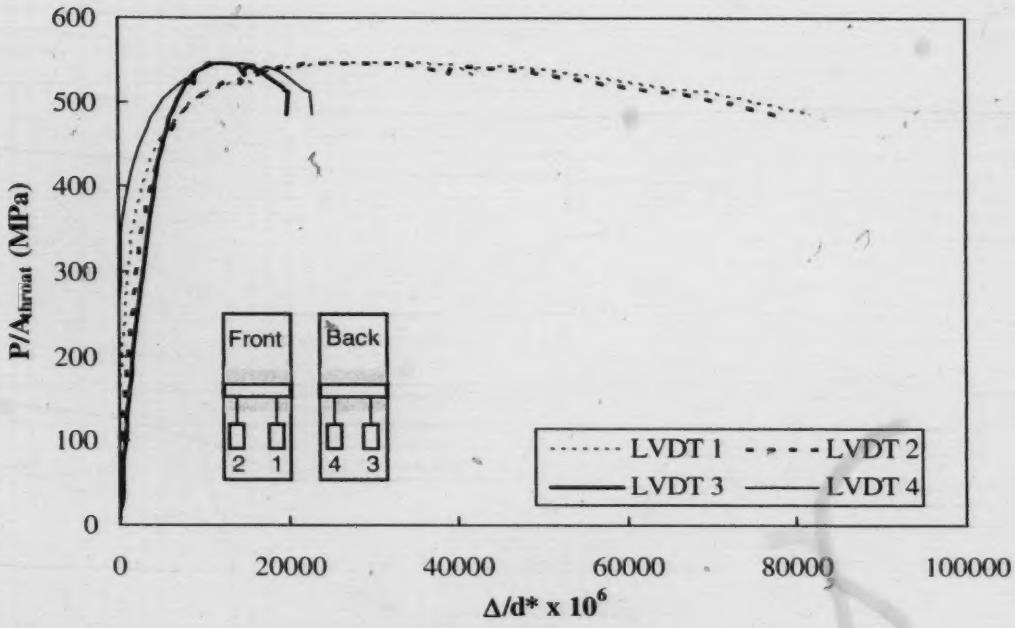



**Figure C0** – Sample Response Curve

## C.2 Response Curves Measured by Strain Gauges

Four strain gauges were applied to each of the six specimens tested at room temperature. The strain gauge locations are shown in Figure C7, which is a duplicate of Figure 3.5. The response curves measured by strain gauges are presented in Figures C8 to C13. In these figures, the applied load is plotted on the vertical axis and the strains recorded by the strain gauges are plotted on the horizontal axis.

Based on an assumed yield strength of the plates of 350 MPa (no material tests were carried out on the base metal) and an elastic modulus of 200 000 MPa, the yield strain of the plates was estimated to be $\varepsilon_y$=1750 microstrain. In Figures C14 to C19, the ratio $P/P_u$ *vs.* the ratio $\varepsilon/\varepsilon_y$ is plotted for the six specimens to show the relationship between the load level and the strain level in the main plates.

Since the strains measured by strain gauges were only affected by the applied tension force and the eccentricity of this force, the average tensile strains were calculated as the average of strain gauges 1 and 4 and the average of strain gauges 2 and 3 (see Figure C7). The average tensile strain, $\varepsilon_t$, is caused by the tensile load. Half of the difference between gauges 1 and 4 and gauges 2 and 3 was treated as the bending strain, $\varepsilon_b$, caused by the eccentricity of the tensile load about the axis parallel to the longitudinal axis of the welds. Figures C20 to C25 present plots of $P/P_u$ *vs.* the ratio $\varepsilon_b/\varepsilon_t$ to show the bending effect caused by main plate misalignment.

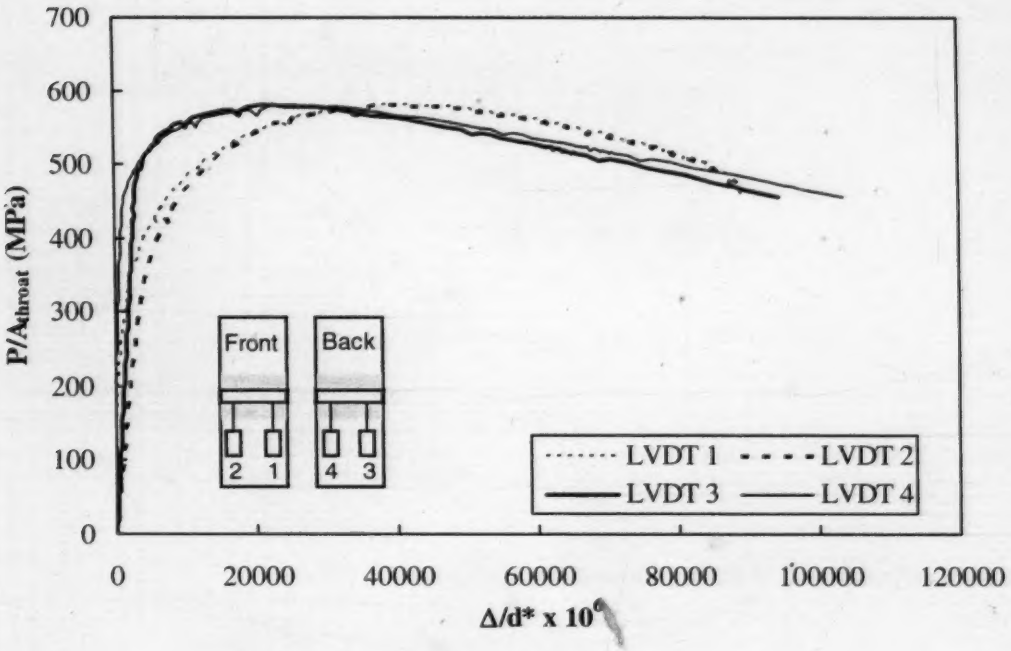



**Figure C1** – Specimen CNY–6 Response Curve

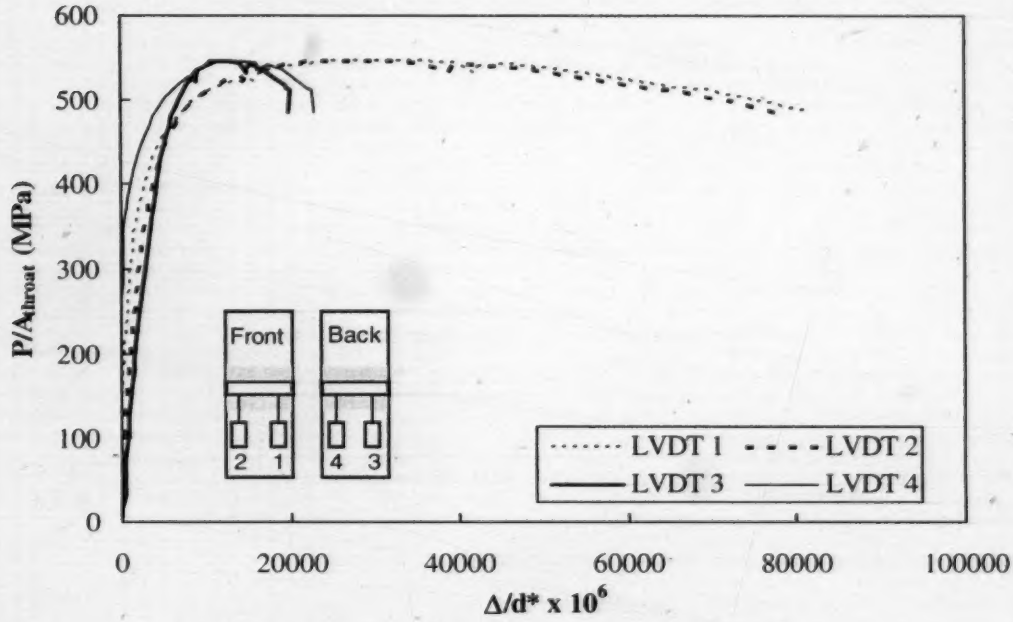



**Figure C2** – Specimen CNY–7 Response Curve

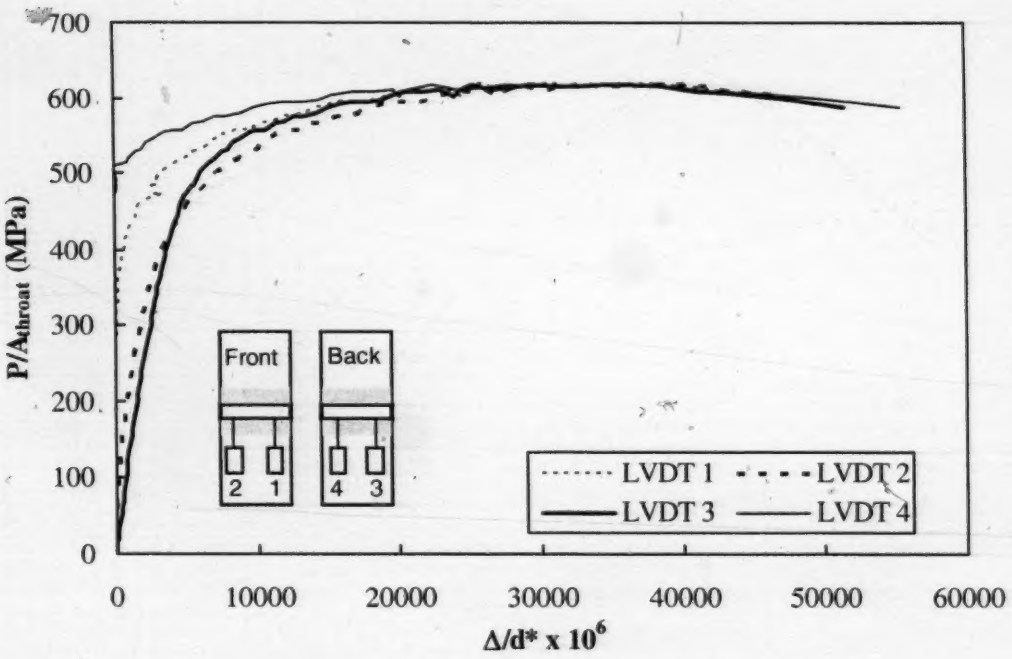



**Figure C3** – Specimen CNY–8 Response Curve

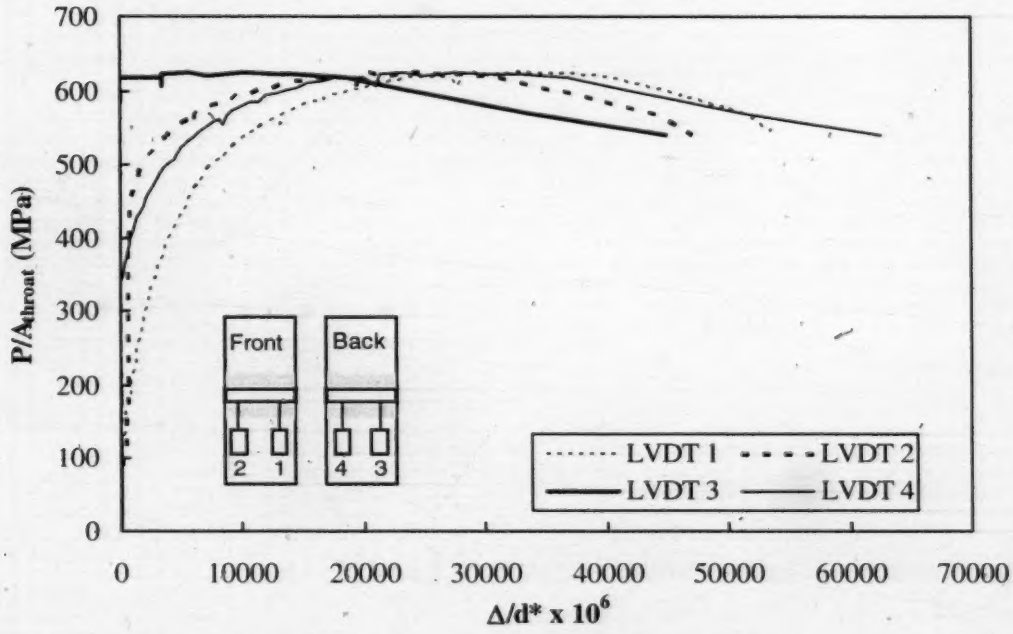



**Figure C4** – Specimen CNY–10 Response Curve

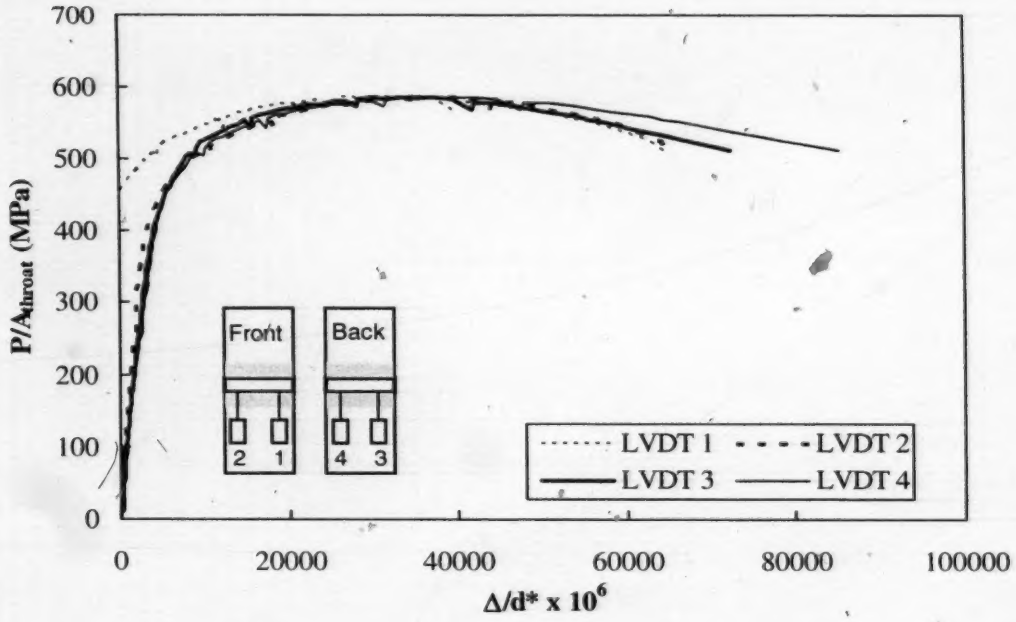



**Figure C5** – Specimen CNY–11 Response Curve

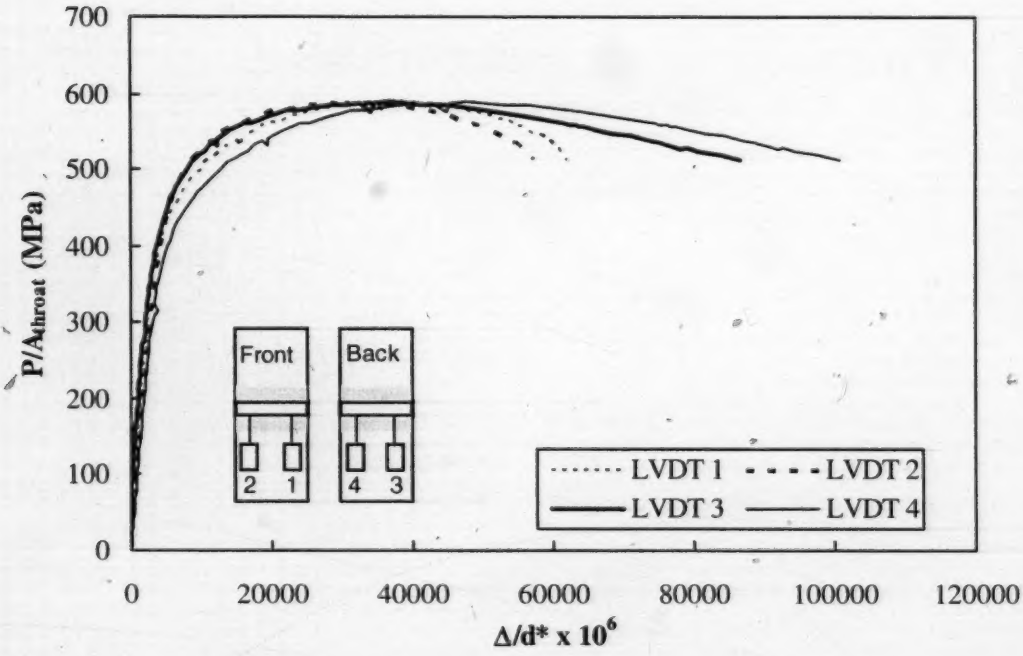
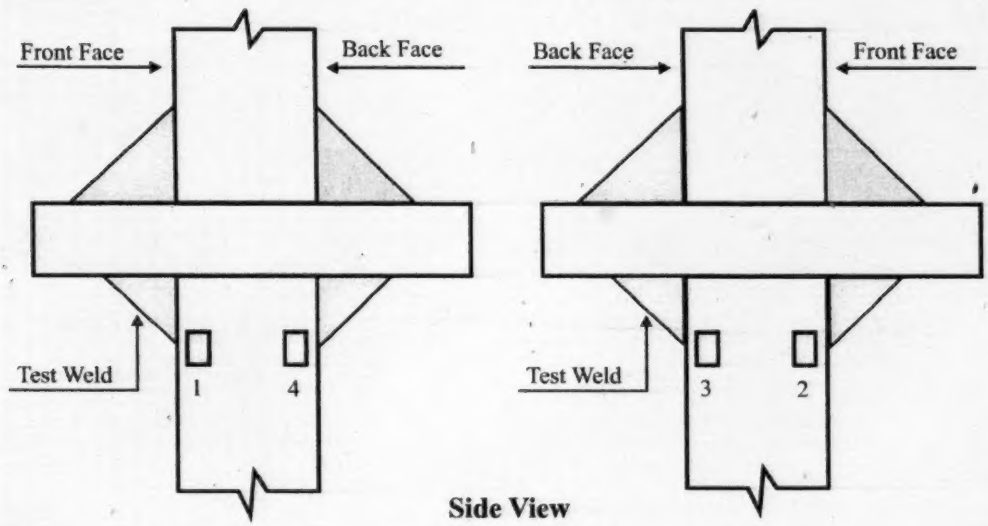
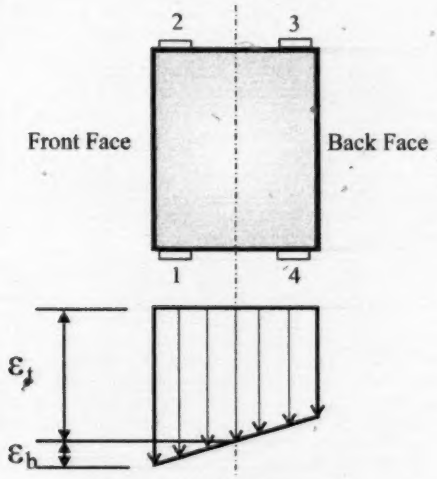



**Figure C6** – Specimen CNY–12 Response Curve




**Side View**




**Top View and Strains**

**Figure C7** – Strain Gauges Arrangement

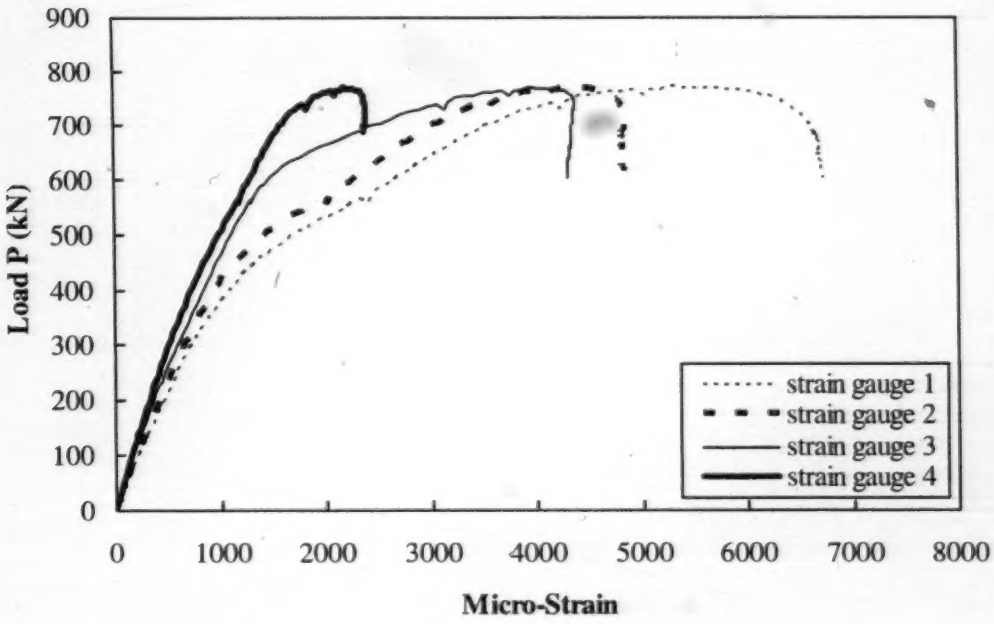



**Figure C8** – Specimen CNY–6 Strain Gauge Measurement

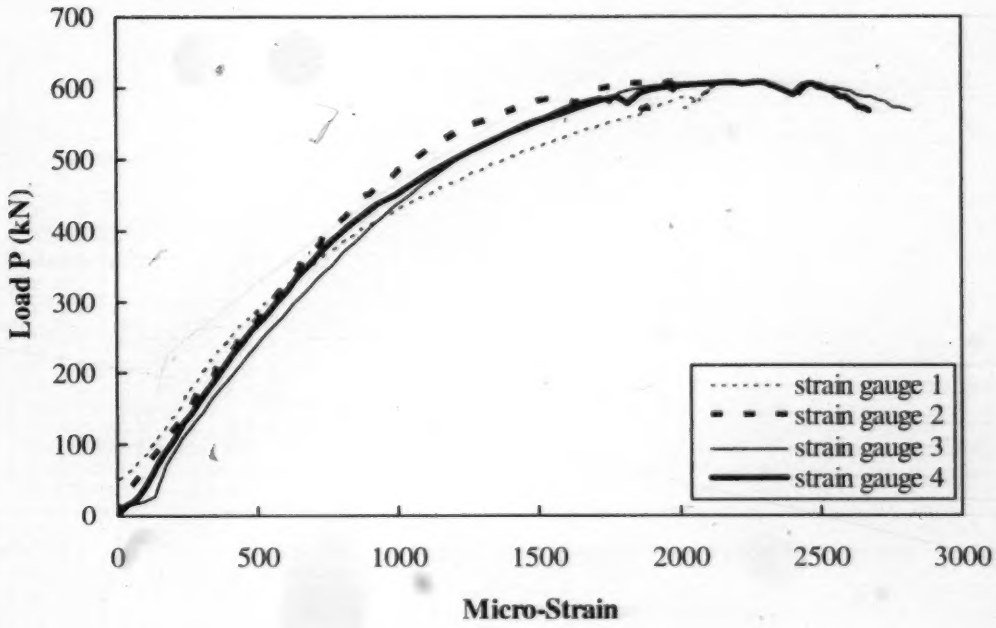



**Figure C9** – Specimen CNY–7 Strain Gauge Measurement

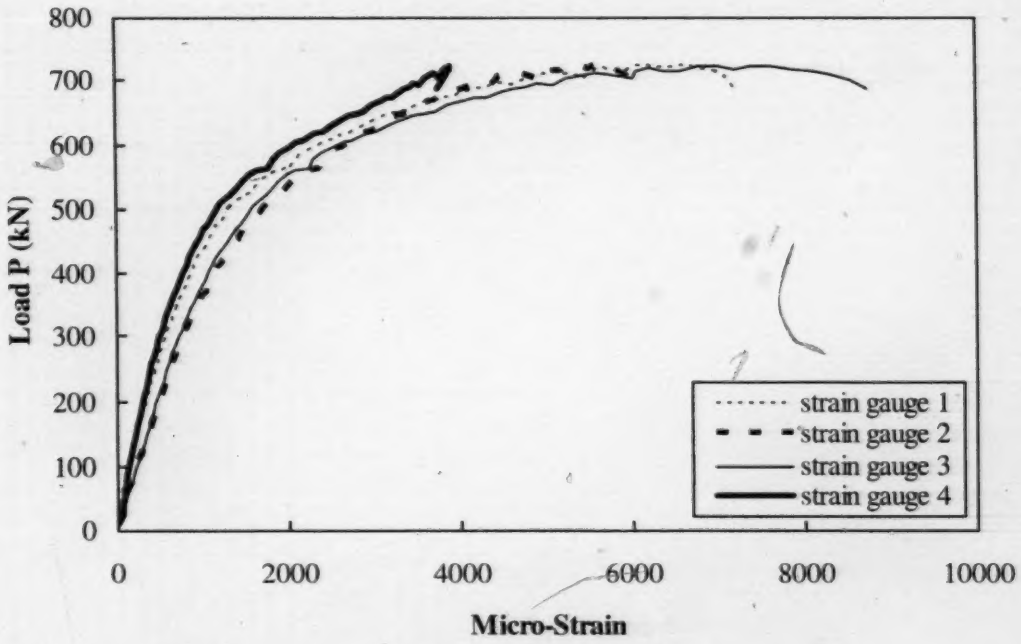



**Figure C10** – Specimen CNY–8 Strain Gauge Measurement

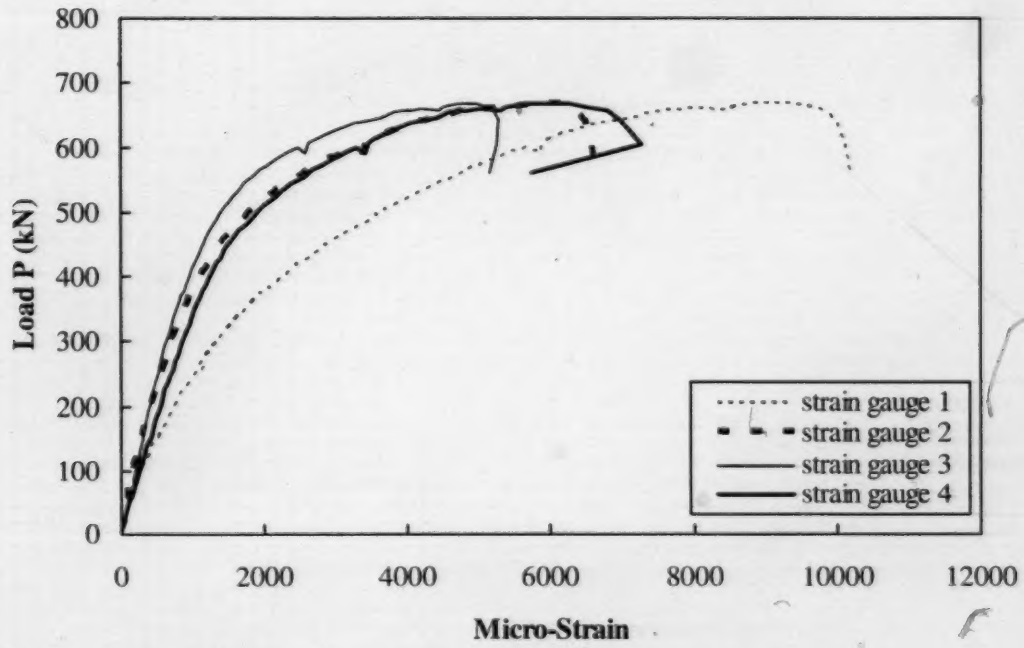



**Figure C11** – Specimen CNY–10 Strain Gauge Measurement

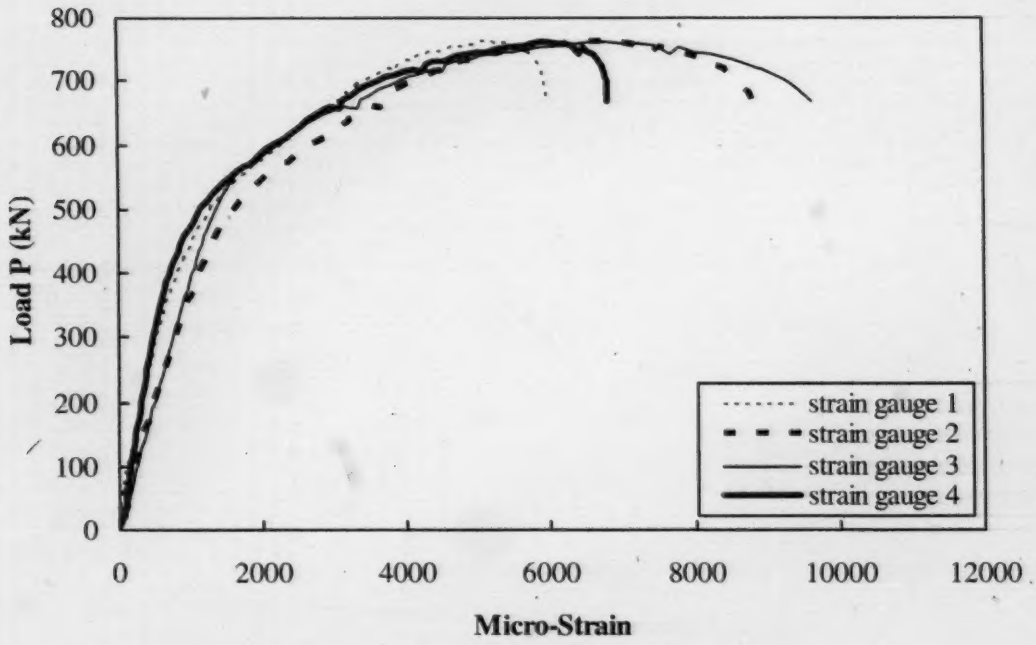



**Figure C12** – Specimen CNY–11 Strain Gauge Measurement

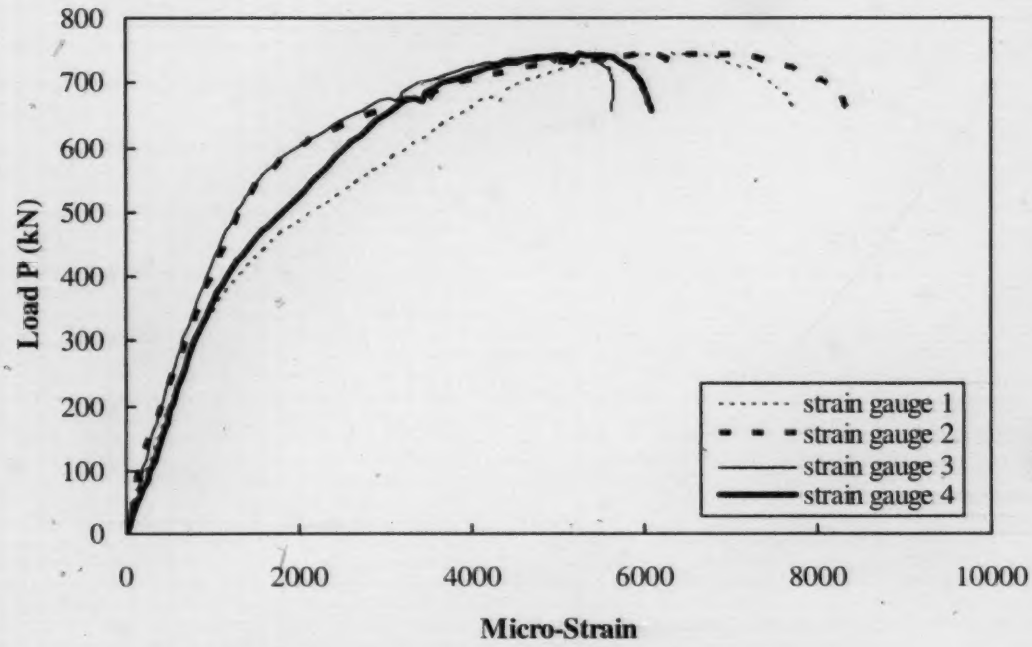



**Figure C13** – Specimen CNY–12 Strain Gauge Measurement

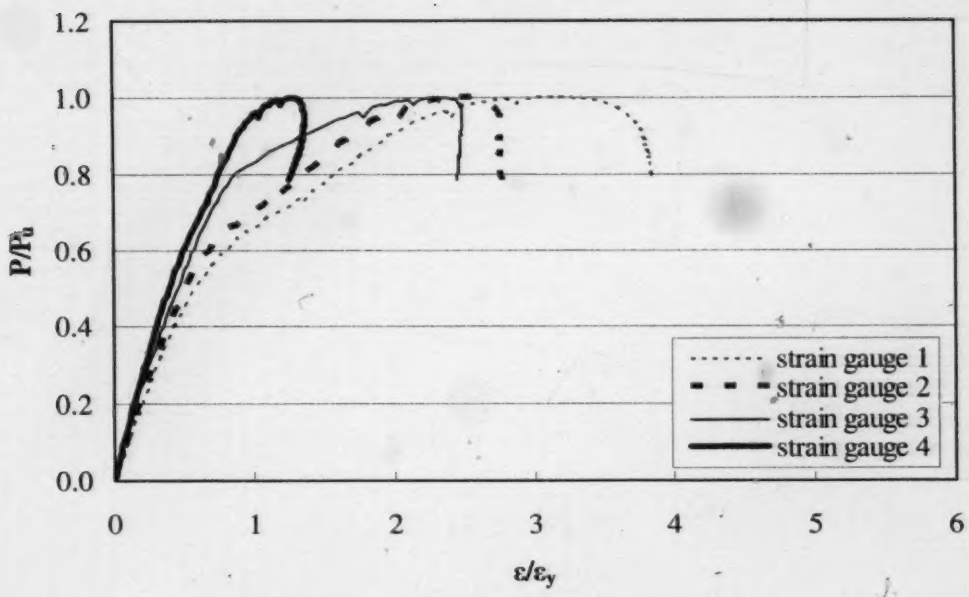



**Figure C14** – $P/P_u$ *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–6

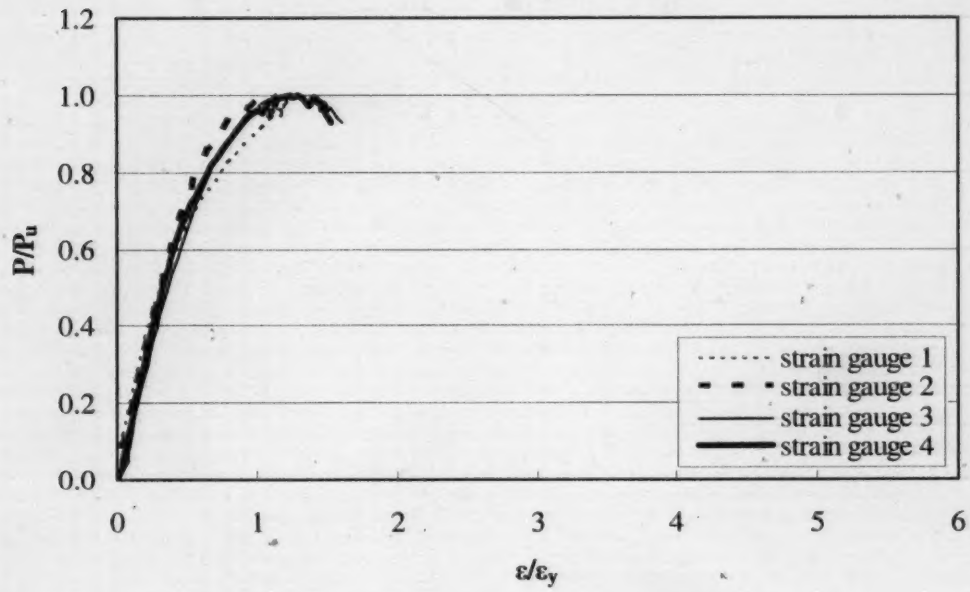



**Figure C15** – $P/P_u$ *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–7

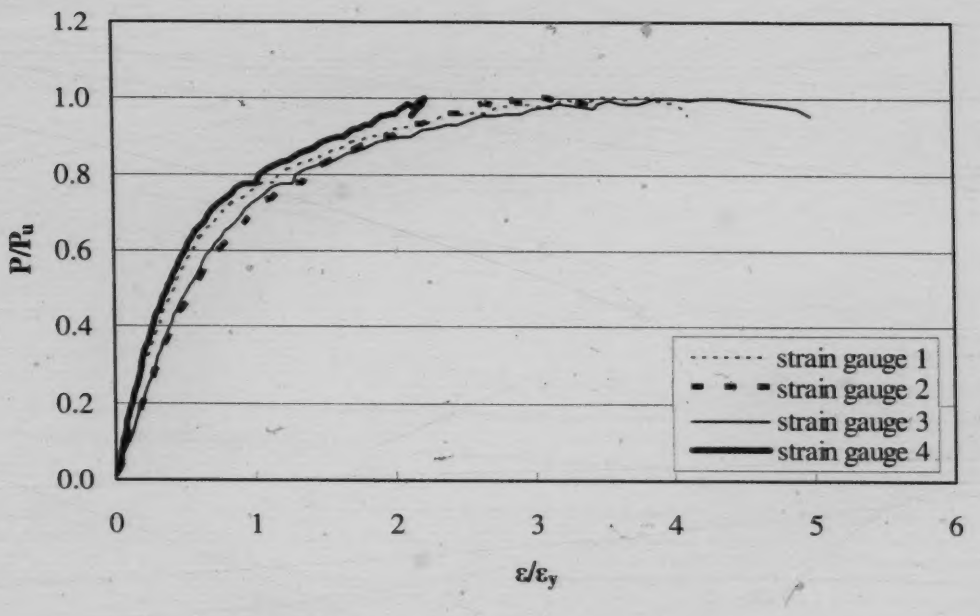



**Figure C16** – $P/P_u$ *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–8

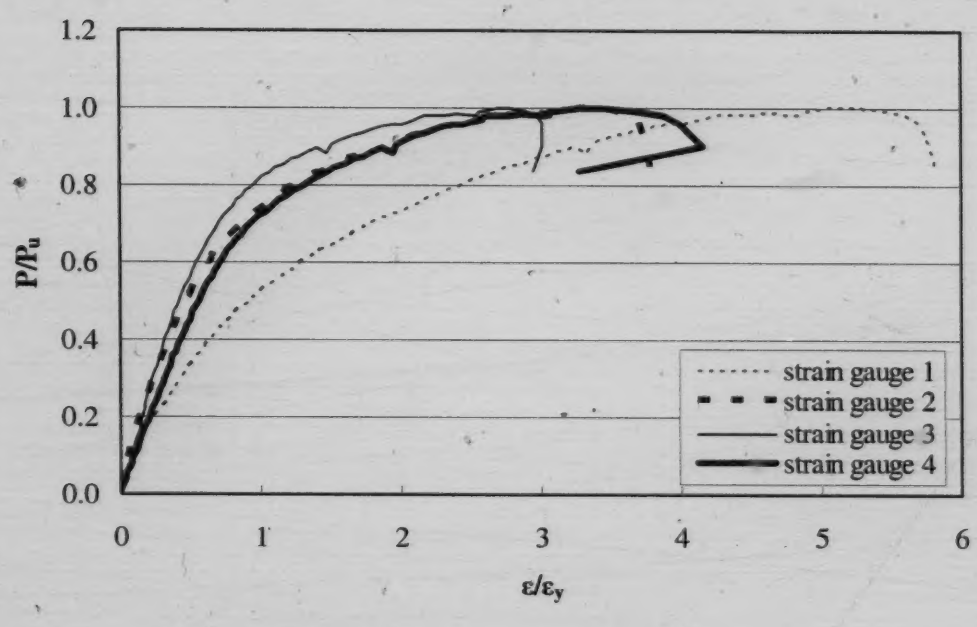



**Figure C17** – $P/P_u$ *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–10

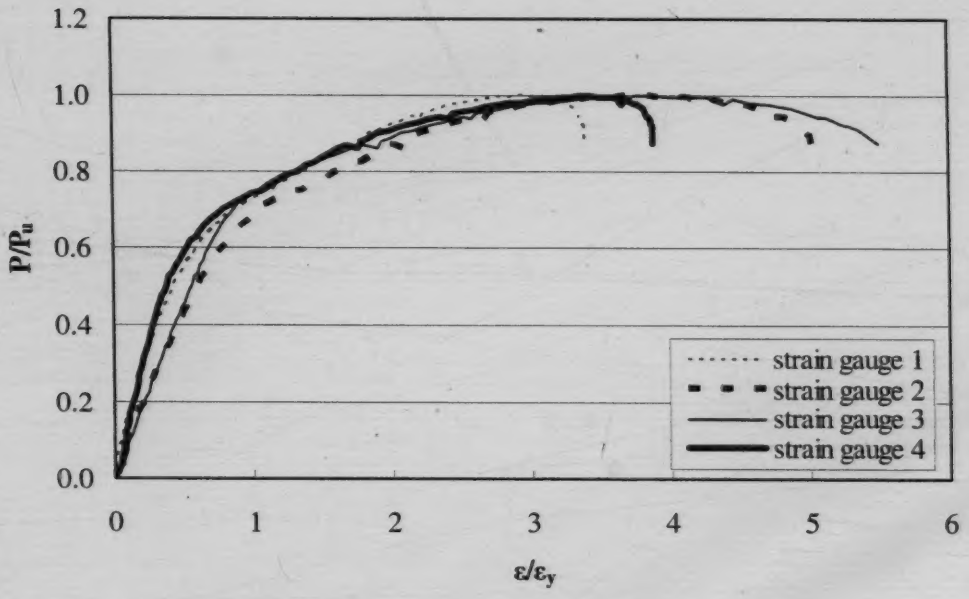



**Figure C18** – $P/P_u$ *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–11

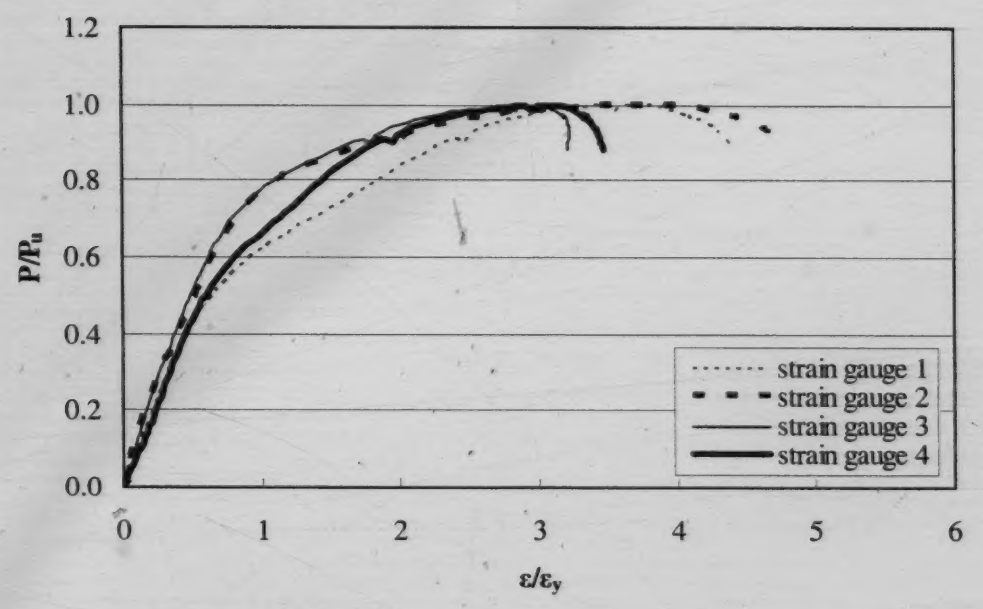



**Figure C19** – $P/P_u$ *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–12

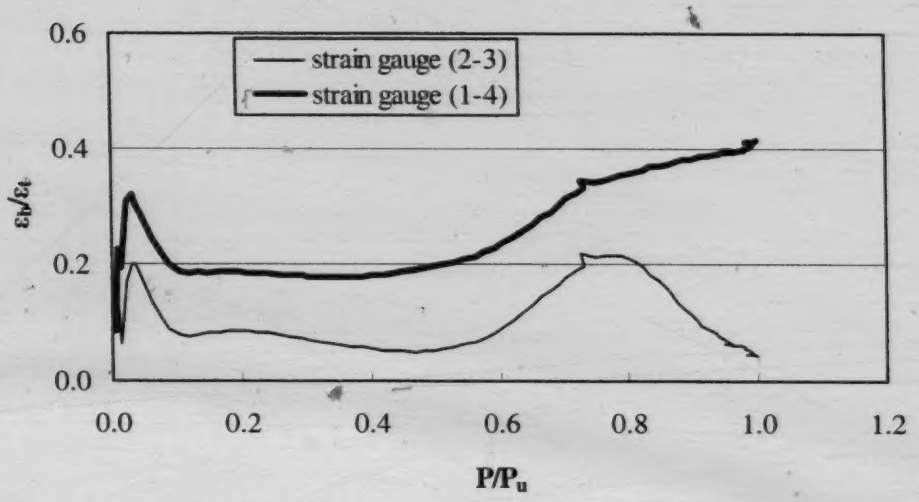



**Figure C20** – $\varepsilon_b/\varepsilon_t$ *vs.* $P/P_u$ of Specimen CNY–6

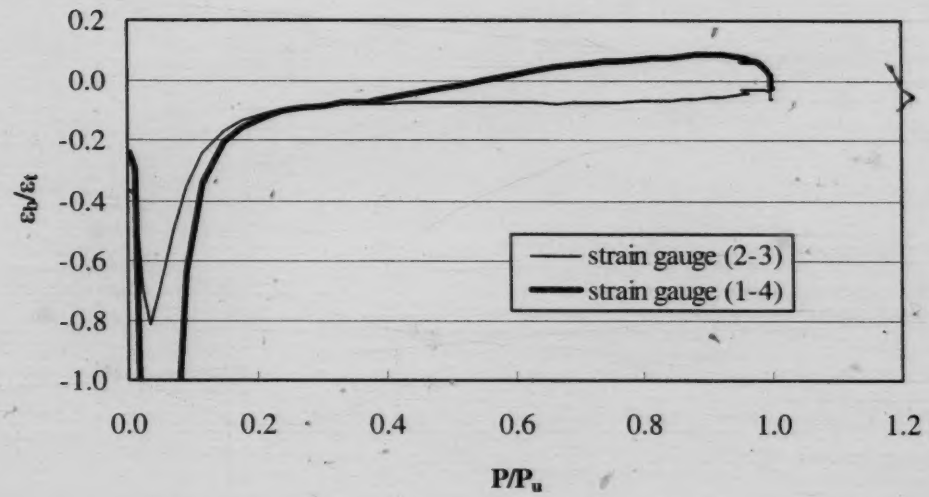



**Figure C21** – $\varepsilon_b/\varepsilon_t$ *vs.* $P/P_u$ of Specimen CNY–7

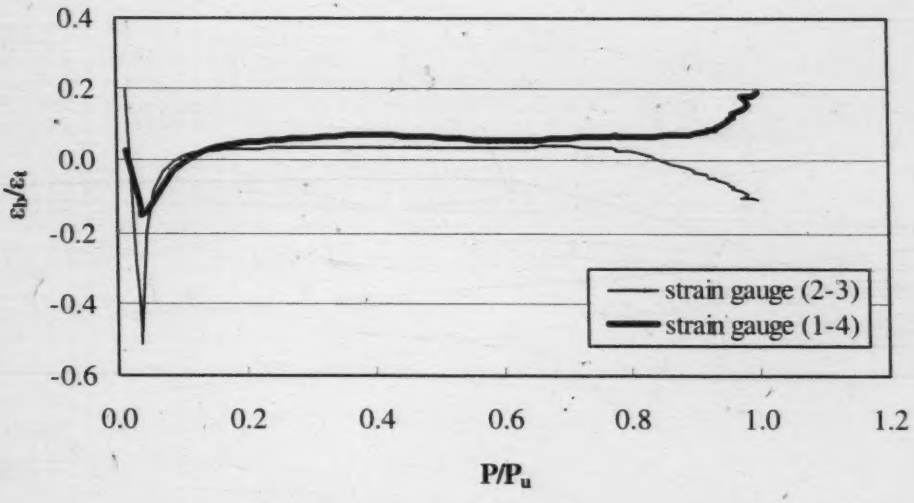



**Figure C22** – $\varepsilon_b/\varepsilon_t$ *vs.* $P/P_u$ of Specimen CNY–8

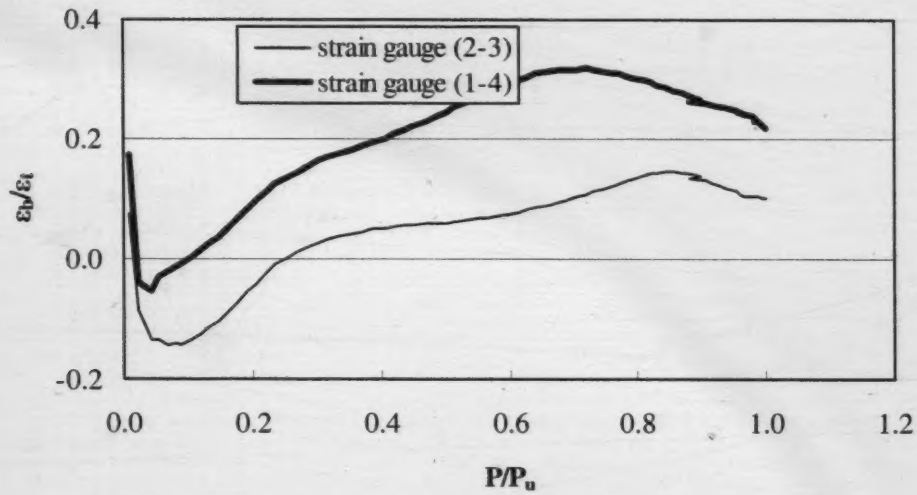



**Figure C23** – $\varepsilon_b/\varepsilon_t$ *vs.* $P/P_u$ of Specimen CNY–10

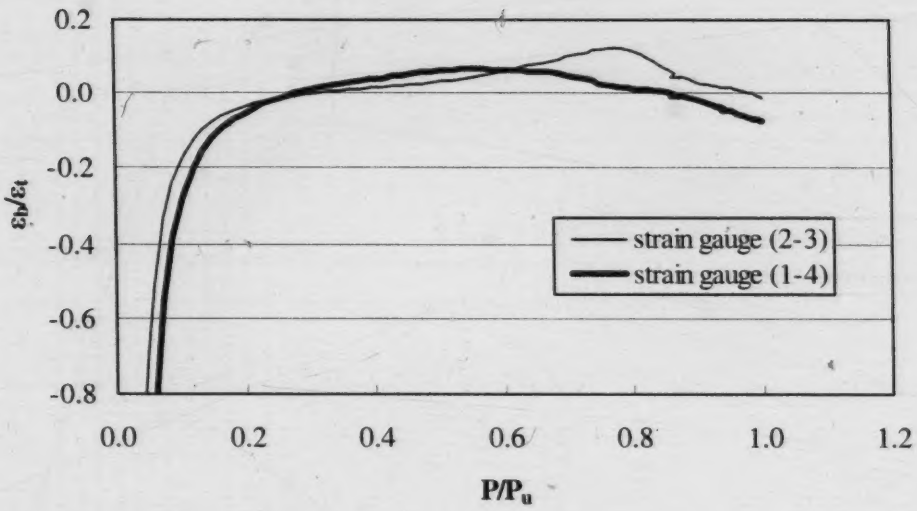



**Figure C24** – $\varepsilon_b/\varepsilon_t$ *vs.* $P/P_u$ of Specimen CNY–11

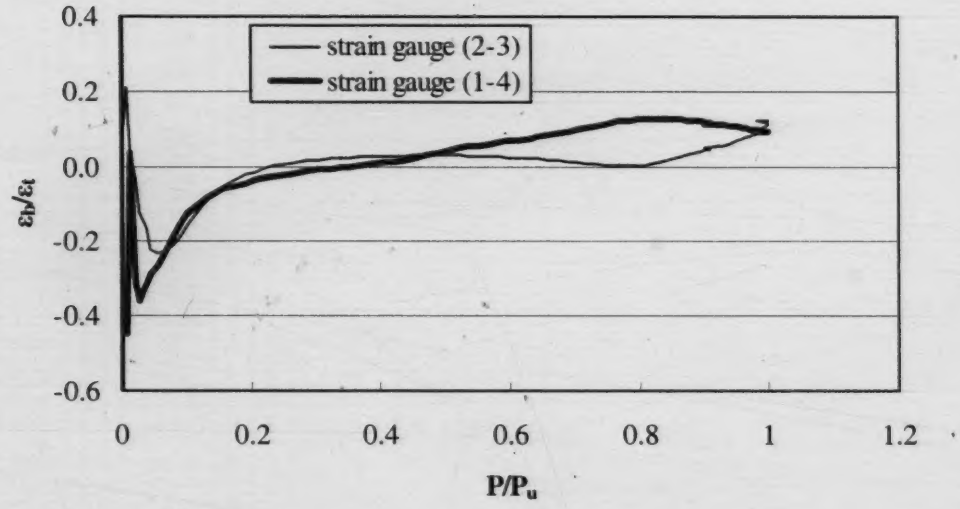



**Figure C25** – $\varepsilon_b/\varepsilon_t$ *vs.* $P/P_u$ of Specimen CNY–12

# APPENDIX D

# RESULTS OF WELD TESTS AT LOW TEMPERATURE

# APPENDIX D

# RESULTS OF WELD TESTS AT LOW TEMPERATURE

## D.1 Introduction

In order to investigate the effect of low temperature on the strength and ductility of cruciform connections, six specimens were tested at -50 °C. The description of those specimens was presented in Chapter 3 and Table 3.1. The specimens tested at low temperature were designed and fabricated in the same way as the specimens tested at room temperature. Unfortunately, all six cruciform specimens failed in main plates. Nevertheless, the test results still provide valuable information about the behaviour of cruciform joints at low temperature.

Low temperature is known to affect the ductility of fillet welds in double lapped fillet weld connections. Ng *et al.* (2002) tested three transverse fillet weld joints at -50 °C made with filler metal without a toughness requirement. The results showed that the ductility of transverse fillet welds was significantly lowered when the welds were tested at low temperature. These three connections had a mean ductility that was only 58% of that of the specimens tested at room temperature. Callele *et al.* (2005) tested three specimens with combined transverse and longitudinal welds at -50 °C. All three specimens failed in the lap plates. Fracture of the lap plates resulted from a combination of a stress concentration, low toughness of the lap plates at low temperature, and shear lag.

From a fracture mechanics point of view, fracture of welds in cruciform joints can be affected by the root notch since the applied load is perpendicular to the root notch. Since fracture toughness decreases with temperature, the behaviour of cruciform joints at low temperature needs to be investigated.

## D.2 Testing Procedure

The test set-up and instrumentation were the same as for other specimens except that a customized environmental chamber, described in detail by Callele *et al.* (2005), was used

to control the test temperature. The specimens and instruments were enclosed in the chamber, in which the temperature was maintained -50 ± 5 ℃.

The specimens were loaded quasi-statically under displacement control. The load and displacements were recorded in real time during the tests. Static load values were acquired by maintaining a constant deformation for about five minutes and the upper load is the extreme large value and the lower load is the extreme small value within the five minute maintenance of the deformation. The static drop is the difference between the upper and lower load. The ultimate load is the extreme large value of load during the entire loading process. The ultimate load may occur within the last five minute maintenance of deformation or after. The upper and lower loads are reported in Table D1.

**D.3 Test Results and Discussion**

All six test specimens failed in the main plates. The measured strengths of the specimens are presented in Table D1. Although fracture took place in the plates, the tabulated strength of the test specimens was calculated as $P_{ST} / A_{throat}$, which is identical to the procedure used in Chapter 3. The measured load versus deformation response curves are shown in Figures D1 to D6. The format of these figures is explained in Appendix C. Although the test specimens failed unexpectedly in the plates rather than in the welds, the load versus deformation curves indicates that the welds might be deforming plastically before rupture of the plates. This indicates that the weld capacity could be reached before the plates fractured. It is inconclusive because the deformation measured by LVDTs included components from both fillet welds and steel plates.

A comparison of the test specimens' strengths recorded at low temperature with those of tests at room temperature is presented in Table D2. The strength of specimens tested at low temperature is approximately the same as that of specimens tested at room temperature.

The root openings of cruciform specimens cause a significant shear lag effect and stress concentration, so the stress in the plates around the fillet weld toe was much higher than the average stress in the plates. The strain gauge measurements for specimens tested at

room temperature demonstrated this phenomenon. The low toughness of the plates at low temperature induced the fracture. For further tests at low temperature, the plates should have sufficient toughness.

**Table D1 –** Summary of Capacity of Specimens Tested at Low Temperature

| Specimen | Electrode | Ultimate Load. $P_u$ (kN) | Static Drop (kN) | | | $P_{ST} = P_u - \Delta P$ (kN) | Throat Area $A_{throat}$ ($mm^2$) | $P_{ST} / A_{throat}$ (MPa) | Average $P_{ST} / A_{throat}$ (MPa) | Initiation of Plate Failure |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | upper | lower | ΔP | | | | | |
| CNY–1 | E70T–7 | 711 | 706 | 694 | 13 | 698 | 1131 | 617 | 587 | Both Faces |
| CNY–5 | | 636 | 624 | 597 | 27 | 609 | 1124 | 542 | | Back Face |
| CNY–9 | | 725 | 652 | 648 | 4 | 721 | 1199 | 601 | | Back Face |
| CNY–2 | E71T8–K6 | 770 | 697 | 691 | 6 | 765 | 1280 | 597 | 583 | Back Face |
| CNY–3 | | 737 | 725 | 718 | 7 | 765 | 1310 | 584 | | Back Face |
| CNY–4 | | 800 | 778 | 763 | 15 | 765 | 1344 | 569 | | Both Faces |

**Table D2** – Comparison of Test Results at Room and Low Temperature

| Specimen | Electrode | Test Temp. | Ultimate Load $P_u$ (kN) | $P_{ST} / A_{throat}$ (MPa) | Average $P_{ST} / A_{throat}$ (MPa) | Strength Ratio -50°C/20°C |
|---|---|---|---|---|---|---|
| CNY–1 | E70T–7 | -50 °C | 711 | 617 | 587 | 0.999 |
| CNY–5 | | | 636 | 542 | | |
| CNY–9 | | | 725 | 601 | | |
| CNY–7 | | 20 °C | 606 | 539 | 588 | |
| CNY–8 | | | 723 | 609 | | |
| CNY–10 | | | 667 | 615 | | |
| CNY–2 | E71T8–K6 | -50 °C | 770 | 597 | 583 | 1.013 |
| CNY–3 | | | 737 | 584 | | |
| CNY–4 | | | 800 | 569 | | |
| CNY–6 | | 20 °C | 770 | 572 | 576 | |
| CNY–11 | | | 760 | 577 | | |
| CNY–12 | | | 744 | 578 | | |

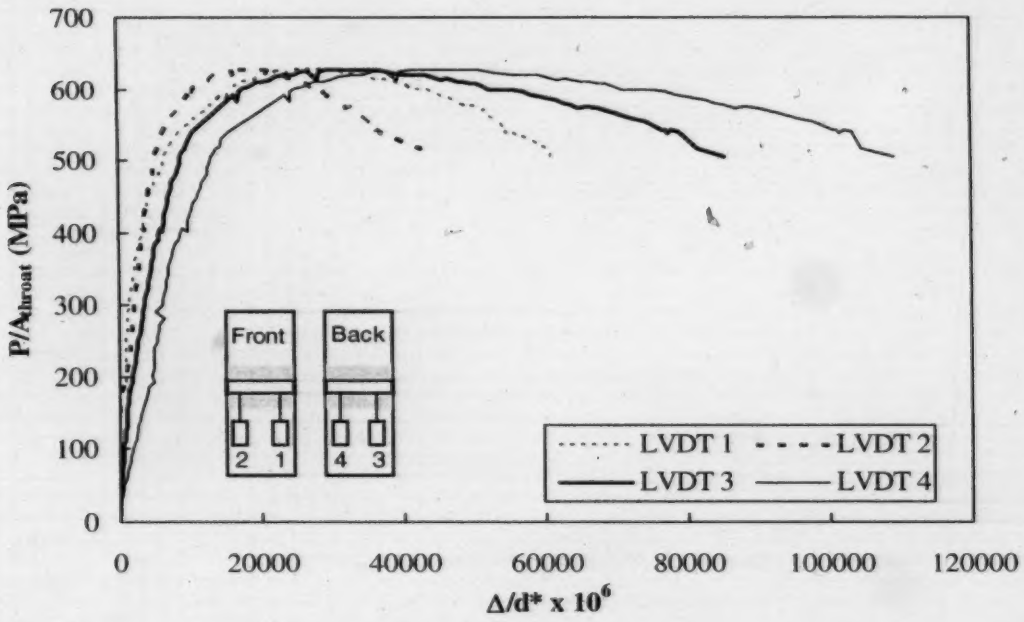



**Figure D1** – Specimen CNY–1 Response Curve

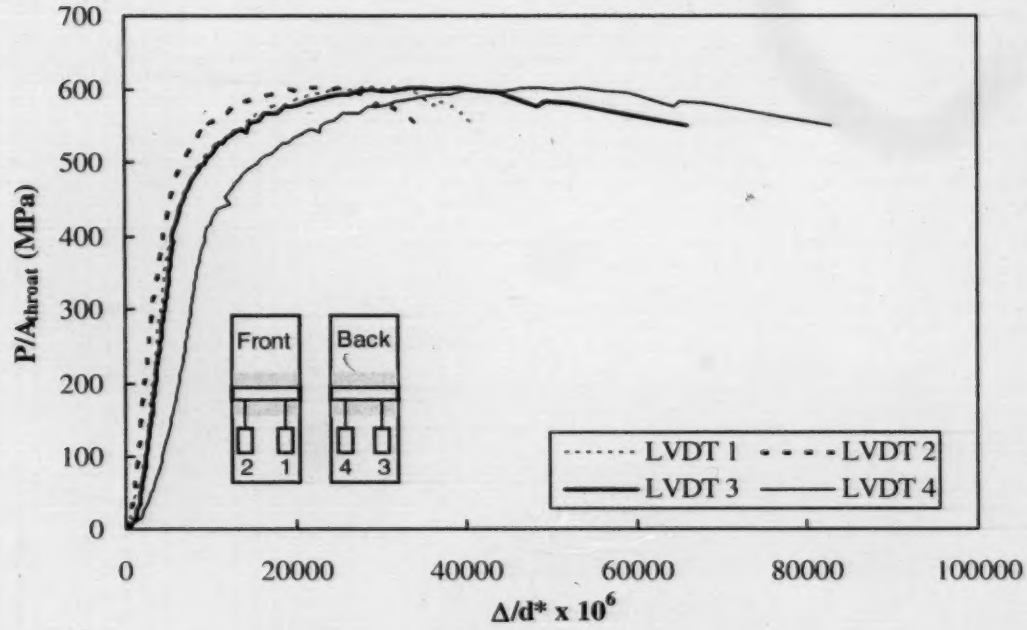



**Figure D2** – Specimen CNY–2 Response Curve

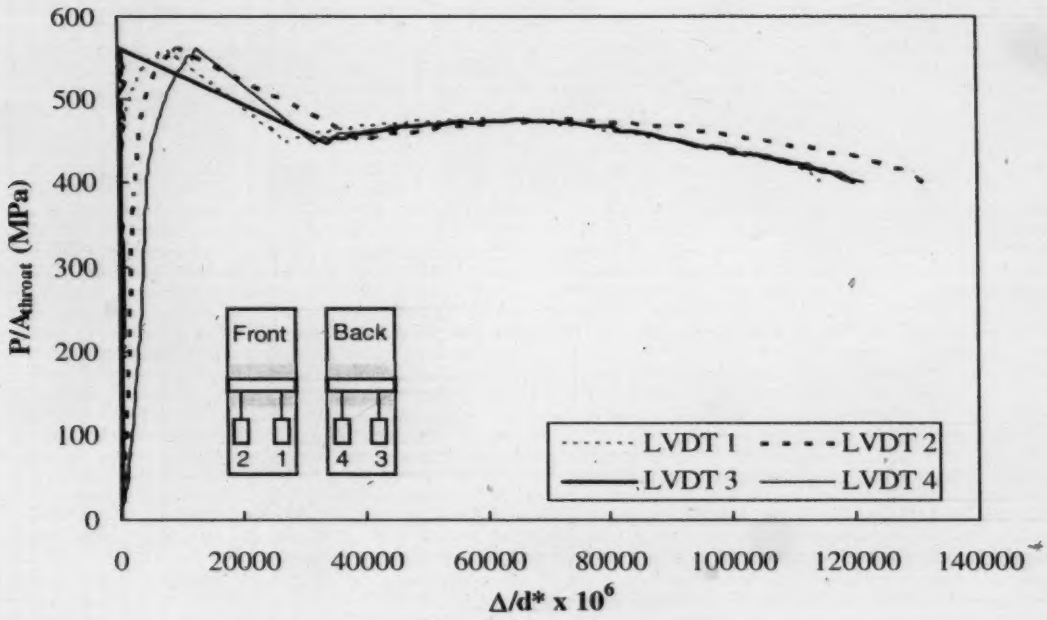



**Figure D3** – Specimen CNY–3 Response Curve

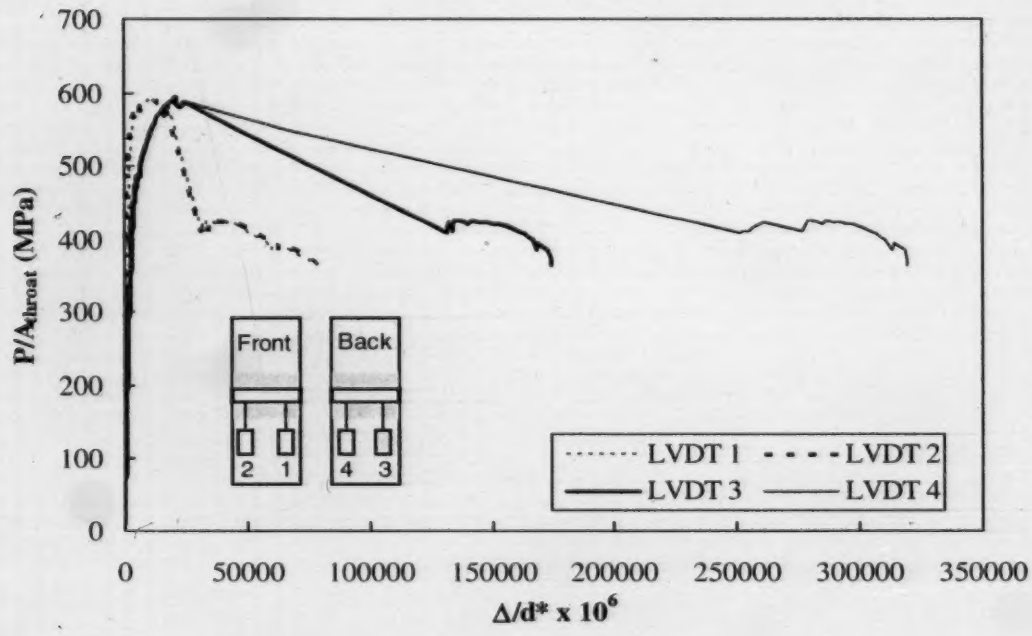



**Figure D4** – Specimen CNY–4 Response Curve

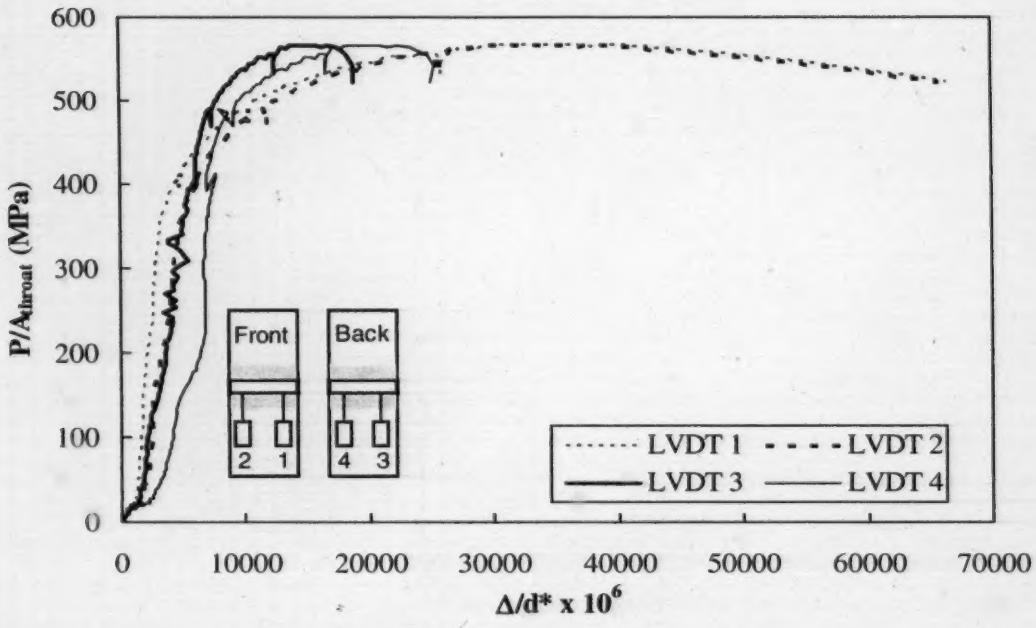



**Figure D5** – Specimen CNY–5 Response Curve

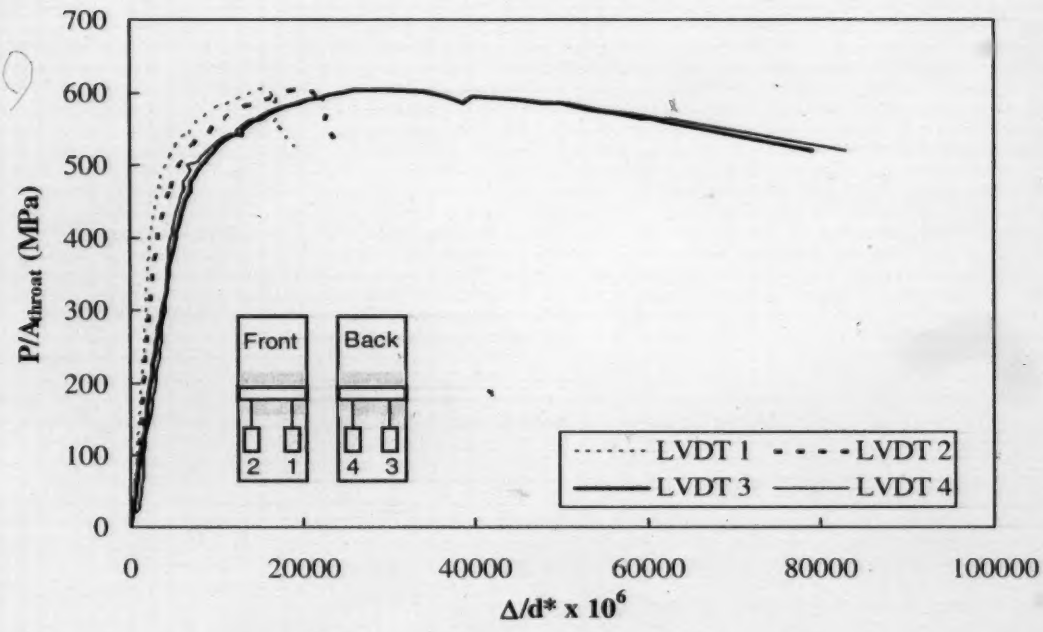



**Figure D6** – Specimen CNY–9 Response Curve

# APPENDIX E

# RESULTS OF OTHER TEST PROGRAMS

# APPENDIX E

# RESULTS OF OTHER TEST PROGRAMS

## E.1 Ligtenberg (1968)

### *E.1.1 Introduction to the Test Series*

Ligtenberg (1968) reported various test series conducted internationally to investigate the strength of fillet welded connections. A total of ten countries participated in this study and each country conducted independent tests under the direction of IIW (International Institute of Welding) documents. The specimens consisted of lapped joints loaded in tension. The general configuration of the specimens is depicted in Figure E1, which illustrates a joint with multiple orientation fillet welds (MOFW). Connections with single orientation fillet welds (SOFW) were also tested. Two types of steel were used in the test program. Approximately 76% of the specimens were fabricated with plates of a quality comparable to St.37 (DIN 17100) (minimum ultimate tensile strength 360 MPa), A7-58 (ASTM A7-58) or similar steel grades from the participating countries. Approximately 24% of the specimens were fabricated with plates of a quality comparable to St.52 (DIN 17100) (minimum ultimate tensile strength 510 MPa) or similar steel. Three types of electrodes (*i.e.* acid coated, basic and rutile), which were locally manufactured and commonly used in the participating country where the tests were performed, were selected. The measured (or reported by manufacturers) weld metal tensile strength ranged from about 450 MPa to 580 MPa and the weld throat size ranged from 3 mm to 10 mm.

### *E.1.2 Test Parameters*

Four factors were considered in the design of the test matrix: the ratio of transverse weld length, $L_1$, to the longitudinal weld length, $L_2$ (see Figure E1), the ratio of the transverse weld throat dimension, $a_1$, to the longitudinal weld throat dimension, $a_2$, the type of electrodes and the predicted stress level in the plates at rupture of the connection, which depends on the plate thickness and the strength of the fillet weld. The variables were chosen as listed below:

the ratio of the weld length $L_1$ to $L_2$:

I: $L_1$=45 mm, $L_2$=80 mm ($L_1 / L_2 = 0.56$)

II: $L_1$=55 mm, $L_2$=55 mm ($L_1 / L_2 = 1.00$)

III: $L_1 = 80$ mm, $L_2 = 40$ mm ($L_1 / L_2 = 2.00$)

the ratio of throat dimension $a_1$ to $a_2$:

$a$: $a_1 = 0.5a_2$

$b$: $a_1 = a_2$

$c$: $a_1 = 2a_2$

the predicted stress level in the plates at rupture:

*s*: small (approximately 150 MPa)

*m*: medium (approximately 200 MPa)

*h*: high (approximately 250 MPa)

the type of electrodes:

*A*: acid coated

*B*: basic

*R*: rutile

The possible 81 combinations of 4 factors listed above are shown in Table E1.1. As indicated in this table, the designation of the general configuration of specimens consists of a roman numeral from I to III indicating the weld length ratio, followed by a three letter designation indicating the weld throat dimension ratio, the plate stress level, and the electrode type. Each of the 9 participating countries tested 9 out of 81 combinations, which were chosen in such a way that every possible combination of any 2 out of the 4 factors occurred once, with the exception that Yugoslavia tested 18 specimens, which repeated some of the specimens tested by the other 9 countries. In order to check the repeatability of the tests between countries, each country conducted tests on the test pieces [IIbmA], [IIbmB] and [IIbmR].

The connections with single orientation welds were tested to examine the force distribution between the different weld segments of a multi-orientation weld. Therefore, in addition to the above general configurations, 4 special configurations were designed, which were designated by adding a number from 1 to 4 into the middle of the basic designation (*e.g.* [xx1xx], [xx2xx], [xx3xx] and [xx4xx], where the first x represents the Roman numeral, regardless of the number of characters it contains). These 4 special configurations used the same parent material, electrode and weld throat dimension and weld length as the corresponding basic configuration [xxxx] except that:

[xx1xx] had only a transverse weld, $a_1$.

[xx2xx] had only two longitudinal welds, $a_2$.

[xx3xx] had only two longitudinal welds with throat dimension, $a_3$, larger than $a_2$.

[xx4xx] had two transverse welds and two longitudinal welds as shown in Figure E2.

A summary of nominal weld throat dimensions, weld length and plate thickness for every configuration is presented in Table E1.2.

Specimens from St.52 steel were prepared from 19 mm and 24 mm plates depending on the material availability and one matching electrode (the grade was not specified in the literature) so the designation of those specimens omitted last two letters. As for St.37 steel specimens the numeral 1, 2, or 3 designates the weld configuration in the test joints.

To get comparable test results, details for the execution of the tests were specified and followed by all participating countries. In order to minimize variability in the test results, all tests conducted within one country had to be performed in one laboratory and with the same equipment. The test specimens were welded manually by a welder of "good average skills" (Ligtenberg 1968). Before testing, the weld throat dimension was measured with a dial gauge at the 45° point of the weld face.

### *E.1.3 Weld Measurements, Test Result and Analysis*

The weld dimensions and test results presented in Tables E1.3 through E1.16 are reproduced from Appendices I and II of Ligtenberg (1968) for different countries and steel grades. The symbols used in these tables are explained below:

$a_1$, $a_2$, $a_4$: weld throat dimension, as shown in Figures E1 and E2.

$a_3$: longitudinal weld throat dimension in a single orientation fillet weld specimen designated as [xx3xx].

$A_1$: $A_1 = \Sigma(a_1 \times L_1)$ for double lapped splice joints as shown in Figure E1 and

$A_1 = a_1 \times L_1$ for single lapped splice joints as shown in Figure E2.

$A_2$: $A_2 = \Sigma(a_2 \times L_2)$.

$A_3$: $A_3 = \Sigma(a_3 \times L_2)$.

$A_4$: $A_4 = a_4 \times L_1$.

$L_1$, $L_2$: weld lengths as shown in Figures E1 and E2.

$P_u$: maximum applied load.

$\sigma_u$: measured ultimate tensile strength of the weld metal.

The geometry factor $\rho_G$ is taken as the ratio of the measured to nominal throat area of the fillet weld segments. A summary of the values of $\rho_G$ for different weld sizes is presented in Table E1.17. Because the geometry factor is calculated from weld throat areas, it reflects variation of both weld throat dimension and weld length. The variation in the length of transverse weld segments, $L_1$, was analyzed and the results are presented in Table E1.18, in which the geometry factor $\rho_L$ is the ratio of the measured to nominal weld length. The results show that the variation of weld length was negligible compared to the variation in throat dimension. Therefore, it is concluded that the results in Table E1.17 are also representative of the variation in weld throat dimension.

The statistical parameters $\rho_{M2}$ and $\rho_P$ were calculated as discussed in Section 4.1, except that the throat areas were calculated from measured throat dimensions instead of from the minimum throat dimension calculated from the measured leg sizes. The results of these calculations are presented in Tables E1.19 through E1.32. The columns with the heading 'Specimen with $a_2$ or $a_3$ only' list the material parameters for the specimens with longitudinal welds only, namely, those of types [xx2xx] and [xx3xx]. The shear strength, $\tau_u$, was obtained by dividing the test capacity, $P_u$, presented in the second column, by the measured weld throat area, $A_2$ or $A_3$, which did not include penetration but included reinforcement. The shear strength predicted from the tensile strength of the filler metal, $\sigma_u$, is listed in column 4, followed by the ratio of column 3 to column 4, $\rho_{M2}$. The columns with the heading 'Specimens with $a_1$ only' list the predicted capacity and the test-to-predicted capacity ratio, $\rho_P$, using Equation 4.7 for the specimens with a transverse weld only, namely, those of type [xx1xx]. The columns with the heading 'Specimens with $a_1$ and $a_2$' list the predicted capacity and the test-to-predicted capacity for test specimens that combined longitudinal and transverse welds. Three different models, presented in Section 4.1, were used to predict the capacity of the test specimens. The columns with the heading 'Specimens with $a_1$, $a_2$ and $a_4$' list the predicted capacity using Equation 4.9 and the test-to-predicted ratio for specimens of the type [xx4xx], which combined longitudinal and transverse welds and were loaded eccentrically in the out-of-plane direction.

The mean values for the ratios $\rho_{M2}$ and $\rho_P$ for the various sources reported by Ligtenberg (1968) are summarized in Table E1.33.

**E.2 Bornscheuer and Feder (1966)**

Bornscheuer and Feder (1966) designed a series of tests to investigate the effects of weld length, weld throat dimension and the ratio of the area of the plate to the area of the weld on fillet weld strength. The test specimens consisted of double lapped joints fabricated in three configurations: (a) connections with longitudinal welds only, (b) connections with

transverse welds only, and (c) five test specimens with the same dimensions as those from group [IIbmR] of the international test series to replicate some of the results from Ligtenberg (1968). The plates were of Fe37 steel and welding was performed with rutile electrodes. The nominal throat dimensions for the specimens with a single weld orientation were 4 mm, 8 mm and 12 mm. The nominal throat dimension for the test specimens with combined transverse and longitudinal welds was 5 mm.

The weld measurements and the test results from Bornscheuer and Feder (1966) are presented in Table E2.1 where $A_{throat}$ is the total measured throat area, which did not include penetration but included reinforcement, and the shear strength $\tau_u$ is equal to $P_u$ divided by $A_{throat}$ for specimen with longitudinal weld only. The geometry factor $\rho_G$ is taken as the ratio of the measured to nominal throat dimension of the fillet weld segments. The professional factor, $\rho_P$, for specimens with only a transverse weld and specimens with transverse and longitudinal welds were calculated as discussed in Section E.1.3 for Tables E1.19 through E1.32. The results of these calculations are presented in Table E2.2.

**E.3 Kato and Morita (1969)**

The tests presented by Kato and Morita (1969) were designed to investigate the effect of weld metal strength, depth of fusion and weld leg size on fillet weld strength. The tests consisted of three groups of connections: specimens with longitudinal welds only, specimens with transverse welds only, and specimens with combined longitudinal and transverse welds.

The test specimens were double lapped joints. The plates were of SM50 steel, which has almost the same properties as St.52 steel, and the welding electrodes were of the basic and rutile types. The measurements and test results are presented in Table E3.1, in which $A_1$ is the measured throat area of transverse welds and $A_2$ is the measured throat area of longitudinal welds. The weld throat area in Table E3.1 was calculated based on the measured throat dimension and did not include root penetration. The geometry factor $\rho_G$ is taken as the ratio of the measured to nominal throat dimension of the fillet weld segments. The statistical parameters $\rho_{M2}$ and $\rho_P$ for specimens with longitudinal welds,

specimens with a transverse weld and specimens with combined transverse and longitudinal welds were calculated as discussed in Section E.1.3 for Tables E1.19 through E1.32. The results of these calculations are presented in Tables E3.2.

**E.4 Butler and Kulak (1969, 1971)**

A series of 23 concentrically loaded double lapped joints and eight full-scale eccentrically loaded connections were tested. The tests on concentrically loaded connections with fillet welds oriented at different angles were conducted to establish the load–deformation response curves for fillet welds loaded at different angles. The test results indicated that both weld capacity and ductility varied with the angle between the axis of the weld and the line of the action of the load. The full-scale tests were eccentrically loaded and were conducted to verify the method of the instantaneous centre of rotation to predict the ultimate capacity of such connections.

Table E4.1 presents a summary of the test specimen parameters and the results are summarized in Table E4.2. Because eccentrically loaded joints are not part of the current study, weld deformations and strength of the full-scale specimen are not presented in Table E4.2. The weld size given in the table represents the average of several measurements. The geometry factor, $\rho_G$, is taken as the ratio of the average measured weld size to nominal weld size of the specimens. The professional factor $\rho_p$ is calculated using Equation 4.7.

**E.5 Dawe and Kulak (1972)**

The main objective of the work presented by Dawe and Kulak (1972) was to develop a method for determining the ultimate strength of eccentrically loaded welded joints in which the weld in the compression zone is not free to rotate. Sixteen such joints, which consisted of three series of different weld configurations, and 15 "weld tension coupons," which were essentially lapped joints of longitudinal welds, were tested. The "weld tension coupons" were tested to establish the load–deformation response for elemental lengths of fillet weld. The electrode used was AWS E60XX and the plates were of ASTM A36 steel. Because no weld-metal coupon tests were conducted in the test program, only

weld size measurements are presented in Table E5.1. The fillet weld leg dimension was taken as the average of 36 individual measurements for each specimen in series A, B and C and 24 measurements for each tension specimen in series 1, 2 and 3. The geometry factor, $\rho_G$, is taken as the ratio of the average measured leg size to nominal leg size of the specimens.

**E.6 Clark (1971)**

Clark (1971) reported a series of 18 tests conducted to investigate the variation of strength and ductility as a function of the angle between the axis of a fillet weld and the applied load. Although details of steel plates and electrodes are not presented in the paper, it is still useful to examine the weld leg size variation and strength variation with the load direction. The results and analysis are presented in Table E6.1. The geometry factor, $\rho_G$, is taken as the ratio of the average measured throat size to nominal throat size of the specimens. The throat area $A_{throat}$ is calculated by multiplying the measured throat size by the weld length. The professional factor, $\rho_p$, is calculated using Equation 4.7.

**E.7 Swannell and Skewes (1979 b)**

Swannell and Skewes (1979b) presented tests that were designed to verify the theoretical ultimate load models and computational techniques for general in-plane loaded weld groups. The nominal weld leg size was 6.4 mm and the measured weld sizes are summarized in Table E7.1. The data presented in the table represent the average of several weld segment measurements. The geometry factor, $\rho_G$, is taken as the ratio of the average measured leg size to nominal leg size of the specimens.

Four series of material tests were conducted. The first series was the all-weld metal tension coupon tests with a cross-sectional area of 100 $mm^2$. The other three series were longitudinal welds in lapped splice joints. The results of the ancillary tests are presented in Table E7.2. The material factor $\rho_{M2}$ is calculated using Equation 4.6a.

**E.8 Pham (1981)**

A total of 25 specimens from three series were tested with the welds loaded eccentrically in plane. Rutile electrodes were used for the preparation of the test specimens. The objective of the test program was to investigate the effect of weld size on the strength of fillet welds. All welding was performed by one welder using run-on and run-off tabs. Because the welded joint specimens were loaded eccentrically, only the weld size measurements are relevant to the current investigation and are listed in Table E8.1. The first letter in the specimen designation indicates the test series, the second letter indicates the specimen type and the third is the sequence number in a test series. Specimen type A had transverse welds loaded eccentrically and specimen type B had longitudinal welds loaded eccentrically. The geometry factor, $\rho_G$, is taken as the ratio of the average measured throat size to nominal throat size of the specimens.

**E.9 Pham (1983a, b)**

Pham tested both cruciform specimens (Pham, 1983a) and Werner specimens (Pham, 1983b) to investigate the effect of weld size on fillet weld strength. The Werner specimens, shown in Figure E3, were designed to eliminate both in-plane and out-of-plane eccentricities for the longitudinal fillet welds tested.

A summary of the test program is presented in Table E9.1 for cruciform test specimens (Pham, 1983a) and Table E9.2 for the Werner specimens (Pham, 1983b).

The fillet weld size measurements are presented in Table E9.3 and Table E9.4. The weld throat measurements presented in the table were measured directly and did not include root penetration. The geometry factor $\rho_G$ is taken as the ratio of the minimum throat dimension (MTD) calculated from the measured leg sizes to the nominal throat size obtained from the nominal leg size.

The test results are summarized in Table E9.5 and Table E9.6, in which $A_{throat}$ is the product of the minimum throat dimension calculated from the measured leg sizes and

measured weld length. The material factor $\rho_{M2}$ is calculated using Equation 4.6a and the professional factor $\rho_P$ is calculated using Equation 4.7.

**E.10 Miazga and Kennedy (1986)**

A series of 42 fillet weld specimens were tested to investigate the effect of loading direction on the strength of fillet welds. The specimens consisted of double lapped joints loaded concentrically and the weld size and plate thicknesses were chosen to ensure that the welds fractured before the plates yielded. Seven loading angles and two weld sizes were examined with three specimens for each combination. The test matrix is presented in Table E10.1.

The fillet weld size measurements and statistical analysis are presented in Table E10.2 and Table E10.3. The geometry factor, $\rho_G$, is taken as the ratio of the average of two measured leg sizes to the nominal leg size of the specimens, since Miazga and Kennedy (1986) only reported the average of the two leg sizes.

The test results were analyzed as shown in Table E10.4. The weld throat areas, $A_{throat}$, were calculated from the average measured leg size and measured weld length. The ultimate tensile strength $\sigma_u = 538\text{MPa}$ was obtained from tests on three all-weld-metal tension coupons. The material factor $\rho_{M2}$ is calculated using Equation 4.6a and the professional factor $\rho_P$ is calculated using Equation 4.7.

**E.11 Quinn (1991) and Bowman and Quinn (1994)**

A series of 18 fillet weld specimens were tested. The variables studied included weld leg size, weld orientation, and fabrication weld root gaps. The specimens were double lapped joints loaded concentrically in tension. The test matrix is shown in Table E11.1.

The weld size measurements are shown in Table E11.2. The geometry factor, $\rho_G$, is taken as the ratio of the minimum throat dimension (MTD) calculated from the measured leg sizes to the nominal throat size obtained from the nominal leg size.

The test results and analysis are shown in Table E11.3, in which the results of specimens with root gaps were not included. The weld throat areas, $A_{throat}$, are the product of the minimum throat dimension calculated from the measured leg sizes and measured weld length. The ultimate tensile strength $\sigma_u = 476$ MPa was obtained by three all-weld-metal tension coupon tests. The material factor $\rho_{M2}$ is calculated per Equation 4.6a and the professional factor $\rho_P$ is calculated per Equation 4.7.

**E.12 Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005)**

The weld leg dimensions reported by Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al.* (2005) are shown in Figure E4. The weld leg on the main plate (MPL) was referred to as the shear leg and the weld leg on the lap plate (LPL) was referred to as the tension leg. The minimum throat dimension (MTD) was calculated from the measured leg sizes using the following equation:

$$\text{MTD} = \frac{\text{MPL} \times \text{LPL}}{\sqrt{\text{MPL}^2 + \text{LPL}^2}} \tag{E.1}$$

The geometric factor, $\rho_G$, is then calculated by using Equation 4.4a, which is represented by the following equation:

$$\rho_G = \text{Mean}\left(\frac{\text{MTD calculated by using Equation (E.1)}}{0.707 \times (\text{nominal weld leg size})}\right) \tag{E.2}$$

Of all the research compiled in this report from the literature, only that of Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al.* (2005) and current test program reported both measured leg and throat dimensions, thereby giving an opportunity to assess directly the degree of face reinforcement in the fillet weld as deposited. Two ratios defined by Equations 4.14a and 4.14b are represented as follows:

$$\alpha_1 = \text{Mean}\left(\frac{45^\circ \text{ Meas}}{\text{MTD}}\right) \tag{E.3}$$

$$\alpha_2 = \text{Mean}\left(\frac{45^\circ \text{ Meas}}{0.707 \times (\text{average of MPL and LPL})}\right) \tag{E.4}$$

The measurements of MPL, LPL, and 45° Meas, the calculated MTD, and the ratios $\alpha_1$, $\alpha_2$, and $\rho_G$ for the specimens of Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005) are presented in Tables E12.1 through E12.5. A summary is presented in Table 4.3.

Results of all-weld-metal tension coupon tests from the various phases of a weld research program reported by Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005) are reproduced in Table E12.6 and the material factor $\rho_{M1}$ is calculated using Equation 4.5.

The results of tests on longitudinal weld specimens from Deng *et al.* (2003) and Callele *et al.* (2005) are presented in Table E12.7 and the material factor $\rho_{M2}$ is calculated using Equation 4.6a.

The test results from specimens with transverse and longitudinal welds from Callele *et al.* (2005) are analyzed in Table E12.8 using three models, as discussed in Section 4.1.

**Table E1.1** – 81 Combinations of 4 Test Parameters for the Test Program Reported by Ligtenberg (1968)

| Test Parameters† | | a | | | b | | | c | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | s | m | h | s | m | h | s | m | h |
| I | A | IasA | IamA | IahA | IbsA | IbmA | IbhA | IcsA | IcmA | IchA |
| | B | IasB | IamB | IahB | IbsB | IbmB | IbhB | IcsB | IcmB | IchB |
| | R | IasR | IamR | IahR | IbsR | IbmR | IbhR | IcsR | IcmR | IchR |
| II | A | IIasA | IIamA | IIahA | IIbsA | IIbmA | IIbhA | IIcsA | IIcmA | IIchA |
| | B | IIasB | IIamB | IIahB | IIbsB | IIbmB | IIbhB | IIcsB | IIcmB | IIchB |
| | R | IIasR | IIamR | IIahR | IIbsR | IIbmR | IIbhR | IIcsR | IIcmR | IIchR |
| III | A | IIIasA | IIIamA | IIIahA | IIIbsA | IIIbmA | IIIbhA | IIIcsA | IIIcmA | IIIchA |
| | B | IIIasB | IIIamB | IIIahB | IIIbsB | IIIbmB | IIIbhB | IIIcsB | IIIcmB | IIIchB |
| | R | IIIasR | IIIamR | IIIahR | IIIbsR | IIIbmR | IIIbhR | IIIcsR | IIIcmR | IIIchR |

† Refer to section E.1.2 for a description of the test parameters

**Table E1.2** – Nominal Dimensions of Test Specimens* from Ligtenberg (1968)

| Specimen Designation† | $L_1$ (mm) | $L_2$ (mm) | $a_1$‡ (mm) | $a_2$ (mm) | $a_3$ (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $t_1$ (mm) | $t_2$ (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| Iasx | | | | | | | | | 24 | 12 |
| Iamx | 45 | 80 | 3 | 5 | 6 | 270 | 1600 | 1920 | 30 | 15 |
| Iahx | | | | | | | | | 38 | 19 |
| Ibsx | | | | | | | | | 19 | 10 |
| Ibmx | 45 | 80 | 3.5 | 3.5 | 4.5 | 315 | 1120 | 1440 | 24 | 12 |
| Ibhx | | | | | | | | | 30 | 15 |
| Icsx | | | | | | | | | 19 | 10 |
| Icmx | 45 | 80 | 6 | 3 | 4 | 540 | 960 | 1280 | 24 | 12 |
| Ichx | | | | | | | | | 30 | 15 |
| IIasx | | | | | | | | | 19 | 10 |
| IIamx | 55 | 55 | 3 | 6 | 7.5 | 330 | 1320 | 1650 | 24 | 12 |
| IIahx | | | | | | | | | 30 | 15 |
| IIbsx | | | | | | | | | 19 | 10 |
| IIbmx | 55 | 55 | 5 | 5 | 7.5 | 550 | 1100 | 1650 | 24 | 12 |
| IIbhx | | | | | | | | | 30 | 15 |
| IIcsx | | | | | | | | | 19 | 10 |
| IIcmx | 55 | 55 | 8 | 4 | 7.5 | 880 | 880 | 1650 | 24 | 12 |
| IIchx | | | | | | | | | 30 | 15 |
| IIIasx | | | | | | | | | 15 | 8 |
| IIIamx | 80 | 40 | 4 | 8 | 10 | 640 | 1280 | 1600 | 19 | 10 |
| IIIahx | | | | | | | | | 24 | 12 |
| IIIbsx | | | | | | | | | 15 | 8 |
| IIIbmx | 80 | 40 | 6 | 6 | 10 | 960 | 960 | 1600 | 19 | 10 |
| IIIbhx | | | | | | | | | 24 | 12 |
| IIIcsx | | | | | | | | | 15 | 8 |
| IIIcmx | 80 | 40 | 8 | 4 | 10 | 1280 | 640 | 1600 | 19 | 10 |
| IIIchx | | | | | | | | | 24 | 12 |

* See Section E.1.3 and Figure E1, E2 for the definition of the symbols in the tables.

† In the designations, x represents R, or A, or B, which are the first letter of the three types of electrodes, *i.e.* Rutile, Acid coated and Basic.

‡ $a_4 = a_1$ for specimens shown in Figure E2.

**Table E1.3** – British Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$ * (mm) | $t_2$ (mm) | $L_1$ † (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia sA | 23.7 | — | 45.0 | 311 | 1709 | — | — | 681 | 451 | w |
| Ia1sA | 23.7 | — | 45.0 | 292 | — | — | — | 182 | 451 | w |
| Ia2sA | 23.7 | — | 45.0 | — | 1770 | — | — | 645 | 451 | w |
| Ia3sA | 23.7 | — | 45.1 | — | — | 2060 | — | 719 | 451 | w |
| Ia4sA | 23.7 | 11.7 | 45.1 | 170 | 827 | — | 138 | 342 | 451 | w |
| Ib mB | 23.8 | — | 45.0 | 390 | 1354 | — | — | 579 | 569 | s |
| Ib1mB | 23.8 | — | 45.0 | 375 | — | — | — | 272 | 569 | w |
| Ib2mB | 23.8 | — | 44.9 | — | 1210 | — | — | 491 | 569 | w |
| Ib3mB | 23.8 | — | 44.9 | — | — | 1529 | — | 539 | 569 | w |
| Ib4mB | 23.8 | 11.6 | 44.8 | 191 | 623 | — | 173 | 318 | 569 | w |
| Ic hR | 30.0 | — | 44.9 | 577 | 1124 | — | — | 712 | 491 | w |
| Ic1hR | 30.0 | — | 44.8 | 521 | — | — | — | 284 | 491 | w |
| Ic2hR | 30.0 | — | 45.0 | — | 1138 | — | — | 429 | 491 | w |
| Ic3hR | 30.0 | — | 44.8 | — | — | 1278 | — | 454 | 491 | w |
| Ic4hR | 30.0 | 15.0 | 45.5 | 269 | 595 | — | 253 | 437 | 491 | w |
| IIa hB | 30.0 | — | 54.9 | 419 | 1438 | — | — | 726 | 569 | w |
| IIa1hB | 30.0 | — | 54.9 | 372 | — | — | — | 187 | 569 | w |
| IIa2hB | 30.0 | — | 54.8 | — | 1483 | — | — | 579 | 569 | w |
| IIa3hB | 30.0 | — | 54.8 | — | — | 1755 | — | 649 | 569 | w |
| IIa4hB | 30.0 | 14.9 | 54.7 | 202 | 660 | — | 194 | 363 | 569 | w |
| IIb sR | 19.0 | — | 54.9 | 601 | 1272 | — | — | 719 | 491 | w |
| IIb1sR | 19.0 | — | 54.9 | 601 | — | — | — | 303 | 491 | w |
| IIb2sR | 19.0 | — | 54.9 | — | 1267 | — | — | 483 | 491 | w |
| IIb3sR | 19.0 | — | 54.9 | — | — | 1711 | — | 590 | 491 | w |
| IIb4sR | 19.0 | 9.8 | 54.7 | 336 | 623 | — | 299 | 405 | 491 | w |
| IIc mA | 23.8 | — | 55.0 | 919 | 966 | — | — | 877 | 451 | w |
| IIc1mA | 23.8 | — | 55.1 | 919 | — | — | — | 507 | 451 | w |
| IIc2mA | 23.8 | — | 54.9 | — | 973 | — | — | 342 | 451 | w |
| IIc3mA | 23.8 | — | 55.0 | — | — | 1702 | — | 645 | 451 | w |
| IIc4mA | 23.8 | 11.6 | 55.2 | 472 | 435 | — | 446 | 525 | 451 | w |
| IIIa mR | 18.9 | — | 80.5 | 779 | 1386 | — | — | 837 | 491 | w |
| IIIa1mR | 18.9 | — | 80.3 | 665 | — | — | — | 316 | 491 | w |
| IIIa2mR | 18.9 | — | 80.4 | — | 1386 | — | — | 437 | 491 | w |
| IIIa3mR | 18.9 | — | 80.2 | — | — | 1680 | — | 507 | 491 | w |
| IIIa4mR | 18.9 | 9.7 | 80.3 | 315 | 704 | — | 340 | 928 | 491 | w |
| IIIb hA | 23.7 | — | 80.7 | 1063 | 1042 | — | — | 930 | 451 | w |
| IIIb1hA | 23.7 | — | 80.3 | 1029 | — | — | — | 592 | 451 | w |
| IIIb2hA | 23.7 | — | 80.3 | — | 1034 | — | — | 381 | 451 | w |
| IIIb3hA | 23.7 | — | 80.7 | — | — | 1713 | — | 545 | 451 | w |
| IIIb4hA | 23.7 | 11.6 | 80.2 | 550 | 514 | — | 507 | 619 | 451 | w |

**Table E1.3 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIc sB | 14.9 | — | 80.1 | 1330 | 701 | — | — | 991 | 569 | s |
| IIIc1sB | 14.9 | — | 80.1 | 1359 | — | — | — | 801 | 569 | w |
| IIIc2sB | 14.9 | — | 80.1 | — | 683 | — | — | 276 | 569 | w |
| IIIc3sB | 14.9 | — | 80.0 | — | — | 1663 | — | 619 | 569 | w |
| IIIc4sB | 14.9 | 8.1 | 80.1 | 664 | 335 | — | 669 | 432 | 569 | w |
| IIbmA 1 | 23.7 | — | 54.8 | 572 | 1152 | — | — | 735 | 451 | w |
| IIbmA 2 | 23.7 | — | 54.9 | 610 | 1194 | — | — | 765 | 451 | w |
| IIbmA 3 | 23.7 | — | 54.9 | 653 | 1230 | — | — | 763 | 451 | w |
| IIbmB 1 | 23.6 | — | 55.0 | 602 | 1190 | — | — | 851 | 569 | s |
| IIbmB 2 | 23.6 | — | 54.8 | 603 | 1243 | — | — | 939 | 569 | w |
| IIbmB 3 | 23.6 | — | 54.8 | 635 | 1144 | — | — | 948 | 569 | w |
| IIbmR 1 | 23.6 | — | 54.8 | 640 | 1307 | — | — | 837 | 491 | w |
| IIbmR 2 | 23.6 | — | 54.8 | 655 | 1325 | — | — | 810 | 491 | w |
| IIbmR 3 | 23.6 | — | 55.0 | 632 | 1177 | — | — | 645 | 491 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.4** – Japanese Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $t_2$ (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia hA | 37.8 | — | 45.0 | 311 | 1391 | — | — | 699 | 446 | w |
| Ia1hA | 37.8 | — | 45.0 | 288 | — | — | — | 202 | 446 | w |
| Ia2hA | 37.8 | — | 45.0 | — | 1356 | — | — | 557 | 446 | w |
| Ia3hA | 37.8 | — | 45.0 | — | — | 1475 | — | 580 | 446 | w |
| Ib sB | 19.3 | — | 45.1 | 406 | 1437 | — | — | 718 | 507 | s |
| Ib1sB | 19.3 | — | 45.1 | 440 | — | — | — | 277 | 507 | w |
| Ib2sB | 19.3 | — | 45.1 | — | 1538 | — | — | 549 | 507 | w |
| Ib3sB | 19.3 | — | 45.1 | — | — | 1678 | — | 586 | 507 | w |
| Ic mR | 24.8 | — | 45.0 | 473 | 961 | — | — | 645 | 560 | w |
| Ic1mR | 24.8 | — | 45.0 | 468 | — | — | — | 262 | 560 | w |
| Ic2mR | 24.8 | — | 45.0 | — | 887 | — | — | 379 | 560 | w |
| Ic3mR | 24.8 | — | 45.0 | — | — | 987 | — | 439 | 560 | w |
| IIa mB | 24.3 | — | 55.1 | 526 | 1496 | — | — | 715 | 507 | w |
| IIa1mB | 24.3 | — | 55.1 | 505 | — | — | — | 297 | 507 | w |
| IIa2mB | 24.3 | — | 55.0 | — | 1515 | — | — | 502 | 507 | w |
| IIa3mB | 24.3 | — | 55.1 | — | — | 1576 | — | 577 | 507 | w |
| IIb hR | 30.0 | — | 55.0 | 462 | 890 | — | — | 554 | 560 | w |
| IIb1hR | 30.0 | — | 55.0 | 489 | — | — | — | 293 | 560 | w |
| IIb2hR | 30.0 | — | 55.0 | — | 990 | — | — | 337 | 560 | w |
| IIb3hR | 30.0 | — | 55.0 | — | — | 1729 | — | 598 | 560 | w |
| IIc sA | 19.1 | — | 55.1 | 682 | 899 | — | — | 746 | 446 | w |
| IIc1sA | 19.1 | — | 55.1 | 666 | — | — | — | 418 | 446 | w |
| IIc2sA | 19.1 | — | 55.0 | — | 896 | — | — | 378 | 446 | w |
| IIc3sA | 19.1 | — | 55.1 | — | — | 972 | — | 369 | 446 | w |
| IIIa sR | 15.7 | — | 80.0 | 560 | 1371 | — | — | 728 | 560 | w |
| IIIa1sR | 15.7 | — | 80.0 | 676 | — | — | — | 387 | 560 | w |
| IIIa2sR | 15.7 | — | 80.0 | — | 1399 | — | — | 477 | 560 | w |
| IIIa3sR | 15.7 | — | 80.0 | — | — | 1606 | — | 549 | 560 | w |
| IIIb mA | 19.1 | — | 80.1 | 776 | 783 | — | — | 752 | 446 | w |
| IIIb1mA | 19.1 | — | 80.1 | 778 | — | — | — | 553 | 446 | w |
| IIIb2mA | 19.1 | — | 80.1 | — | 814 | — | — | 302 | 446 | w |
| IIIb3mA | 19.1 | — | 80.2 | — | — | 1276 | — | 454 | 446 | w |
| IIIc hB | 25.8 | — | 80.1 | 1416 | 817 | — | — | 908 | 507 | w |
| IIIc1hB | 25.8 | — | 80.1 | 1416 | — | — | — | 694 | 507 | w |
| IIIc2hB | 25.8 | — | 80.1 | — | 831 | — | — | 285 | 507 | w |
| IIIc3hB | 25.8 | — | 80.1 | — | — | 1720 | — | 548 | 507 | w |

**Table E1.4 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIbmA 1 | 24.6 | — | 55.1 | 517 | 884 | — | — | 613 | 446 | w |
| IIbmA 2 | 24.6 | — | 55.0 | 496 | 886 | — | — | 604 | 446 | w |
| IIbmA 3 | 24.6 | — | 55.1 | 489 | 893 | — | — | 615 | 446 | w |
| IIbmB 1 | 24.7 | — | 54.7 | 617 | 1243 | — | — | 730 | 507 | s |
| IIbmB 2 | 24.7 | — | 54.8 | 606 | 1296 | — | — | 736 | 507 | w |
| IIbmB 3 | 24.7 | — | 54.8 | 663 | 1292 | — | — | 743 | 507 | w |
| IIbmR 1 | 24.9 | — | 55.0 | 473 | 946 | — | — | 619 | 560 | w |
| IIbmR 2 | 24.9 | — | 55.0 | 446 | 938 | — | — | 606 | 560 | w |
| IIbmR 3 | 24.9 | — | 55.0 | 462 | 909 | — | — | 610 | 560 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.5** – USA Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$ * (mm) | $t_2$ (mm) | $L_1$ † (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia mR | 32.7 | — | 45.0 | 302 | 1350 | — | — | 557 | 472 | w |
| Ia1mR | 32.7 | — | 45.1 | 323 | — | — | — | 169 | 472 | w |
| Ia2mR | 32.7 | — | 45.0 | — | 1428 | — | — | 490 | 472 | w |
| Ia3mR | 32.7 | — | 45.0 | — | — | 1570 | — | 533 | 472 | w |
| Ia4mR | 32.7 | 15.6 | 45.1 | 161 | 637 | — | 154 | 381 | 472 | w |
| Ib hA | 32.7 | — | 45.1 | 347 | 997 | — | — | 659 | 454 | w |
| Ib1hA | 32.7 | — | 45.1 | 358 | — | — | — | 238 | 454 | w |
| Ib2hA | 32.7 | — | 45.1 | — | 1140 | — | — | 511 | 454 | w |
| Ib3hA | 32.7 | — | 45.2 | — | — | 1462 | — | 575 | 454 | w |
| Ib4hA | 32.7 | 15.6 | 45.0 | 171 | 514 | — | 160 | 383 | 454 | w |
| Ic sB | 18.9 | — | 45.1 | 526 | 1028 | — | — | 713 | 545 | w |
| Ic1sB | 18.9 | — | 45.1 | 531 | — | — | — | 291 | 545 | w |
| Ic2sB | 18.9 | — | 45.0 | — | 1007 | — | — | 499 | 545 | w |
| Ic3sB | 18.9 | — | 45.0 | — | — | 1306 | — | 617 | 545 | w |
| Ic4sB | 18.9 | 9.5 | 45.0 | 246 | 495 | — | 240 | 342 | 545 | w |
| IIa sA | 18.9 | — | 55.0 | 323 | 1146 | — | — | 604 | 454 | w |
| IIa1sA | 18.9 | — | 55.1 | 357 | — | — | — | 227 | 454 | w |
| IIa2sA | 18.9 | — | 55.0 | — | 1095 | — | — | 395 | 454 | w |
| IIa3sA | 18.9 | — | 55.1 | — | — | 1460 | — | 523 | 454 | w |
| IIa4sA | 18.9 | 9.5 | 55.0 | 150 | 601 | — | 154 | 303 | 454 | w |
| IIb mB | 25.8 | — | 55.1 | 497 | 934 | — | — | 684 | 545 | w |
| IIb1mB | 25.8 | — | 55.1 | 565 | — | — | — | 363 | 545 | w |
| IIb2mB | 25.8 | — | 55.0 | — | 965 | — | — | 414 | 545 | w |
| IIb3mB | 25.8 | — | 55.1 | — | — | 1550 | — | 666 | 545 | w |
| IIb4mB | 25.8 | 12.7 | 55.0 | 244 | 456 | — | 222 | 462 | 545 | w |
| IIc hA | 32.7 | — | 55.0 | 831 | 801 | — | — | 715 | 472 | w |
| IIc1hA | 32.7 | — | 55.0 | 880 | — | — | — | 445 | 472 | w |
| IIc2hA | 32.7 | — | 54.9 | — | 859 | — | — | 325 | 472 | w |
| IIc3hA | 32.7 | — | 55.1 | — | — | 1700 | — | 597 | 472 | w |
| IIc4hA | 32.7 | 15.6 | 55.1 | 434 | 384 | — | 444 | 581 | 472 | w |
| IIIa hB | 25.8 | — | 79.8 | 640 | 1047 | — | — | 951 | 545 | w |
| IIIa1hB | 25.8 | — | 80.1 | 689 | — | — | — | 543 | 545 | w |
| IIIa2hB | 25.8 | — | 80.0 | — | 1009 | — | — | 470 | 545 | w |
| IIIa3hB | 25.8 | — | 80.0 | — | — | 1437 | — | 615 | 545 | w |
| IIIa4hB | 25.8 | 12.7 | 80.0 | 316 | 579 | — | 288 | 575 | 545 | w |
| IIIb sR | 15.6 | — | 80.0 | 745 | 790 | — | — | 710 | 472 | w |
| IIIb1sR | 15.6 | — | 80.0 | 815 | — | — | — | 461 | 472 | w |
| IIIb2sR | 15.6 | — | 80.1 | — | 841 | — | — | 292 | 472 | w |
| IIIb3sR | 15.6 | — | 80.0 | — | — | 1352 | — | 471 | 472 | w |
| IIIb4sR | 15.6 | 7.9 | 80.0 | 323 | 342 | — | 325 | 399 | 472 | w |

**Table E1.5 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIc mA | 18.9 | — | 80.1 | 1293 | 608 | — | — | 890 | 454 | w |
| IIIc1mA | 18.9 | — | 80.0 | 1347 | — | — | — | 708 | 454 | w |
| IIIc2mA | 18.9 | — | 80.0 | — | 590 | — | — | 303 | 454 | w |
| IIIc3mA | 18.9 | — | 80.0 | — | — | 1390 | — | 539 | 454 | w |
| IIIc4mA | 18.9 | 9.5 | 80.0 | 518 | 313 | — | 367 | 497 | 454 | w |
| IIbmA 1 | 25.7 | — | 55.1 | 605 | 1086 | — | — | 734 | 454 | w |
| IIbmA 2 | 25.7 | — | 55.0 | 580 | 1107 | — | — | 774 | 454 | w |
| IIbmA 3 | 25.7 | — | 55.1 | 639 | 1157 | — | — | 757 | 454 | w |
| IIbmB 1 | 25.8 | — | 55.0 | 510 | 972 | — | — | 742 | 545 | w |
| IIbmB 2 | 25.8 | — | 55.0 | 462 | 916 | — | — | 744 | 545 | w |
| IIbmB 3 | 25.8 | — | 55.1 | 517 | 966 | — | — | 726 | 545 | w |
| IIbmR 1 | 25.8 | — | 55.1 | 482 | 997 | — | — | 606 | 472 | w |
| IIbmR 2 | 25.8 | — | 55.1 | 450 | 923 | — | — | 619 | 472 | w |
| IIbmR 3 | 25.8 | — | 55.1 | 506 | 937 | — | — | 601 | 472 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.6** – French Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$ * (mm) | $t_2$ (mm) | $L_1$ † (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode ‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia hB | 37.6 | — | 45.0 | 315 | 1581 | — | — | 785 | 516 | — |
| Ia1hB | 37.6 | — | 45.0 | 279 | — | — | — | 155 | 516 | — |
| Ia2hB | 37.6 | — | 46.0 | — | 1700 | — | — | 618 | 516 | — |
| Ia3hB | 37.6 | — | 45.0 | — | — | 2060 | — | 697 | 516 | — |
| Ia4hB | 37.6 | 19.0 | 46.0 | 127 | 760 | — | 150 | 383 | 516 | — |
| IbsR | 19.0 | — | 47.0 | 282 | 960 | — | — | 667 | 563 | — |
| Ib1sR | 19.0 | — | 46.0 | 299 | — | — | — | 196 | 563 | — |
| Ib2sR | 19.0 | — | 46.0 | — | 1140 | — | — | 500 | 563 | — |
| Ib3sR | 19.0 | — | 45.0 | — | — | 1360 | — | 515 | 563 | — |
| Ib4sR | 19.0 | 10.5 | 45.0 | 135 | 544 | — | 124 | 309 | 563 | — |
| Ic mA | 24.0 | — | 46.0 | 560 | 1060 | — | — | 755 | 494 | — |
| Ic1mA | 24.0 | — | 47.0 | 634 | — | — | — | 353 | 494 | — |
| Ic2mA | 24.0 | — | 45.0 | — | 1056 | — | — | 451 | 494 | — |
| Ic3mA | 24.0 | — | 47.0 | — | — | 1312 | — | 491 | 494 | — |
| Ic4mA | 24.0 | 12.0 | 46.0 | 276 | 512 | — | 276 | 383 | 494 | — |
| IIa mR | 24.0 | — | 57.0 | 342 | 1210 | — | — | 608 | 563 | — |
| IIa1mR | 24.0 | — | 56.0 | 325 | — | — | — | 216 | 563 | — |
| IIa2mR | 24.0 | — | 56.0 | — | 1360 | — | — | 491 | 563 | — |
| IIa3mR | 24.0 | — | 56.0 | — | — | 1590 | — | 569 | 563 | — |
| IIa4mR | 24.0 | 12.0 | 56.0 | 168 | 671 | — | 168 | 373 | 563 | — |
| IIb hA | 29.7 | — | 57.0 | 570 | 1100 | — | — | 834 | 494 | — |
| IIb1hA | 29.7 | — | 56.0 | 549 | — | — | — | 341 | 494 | — |
| IIb2hA | 29.7 | — | 57.0 | — | 990 | — | — | 461 | 494 | — |
| IIb3hA | 29.7 | — | 55.0 | — | — | 1630 | — | 638 | 494 | — |
| IIb4hA | 29.7 | 15.0 | 57.0 | 285 | 550 | — | 270 | 491 | 494 | — |
| IIc sB | 19.0 | — | 56.0 | 896 | 792 | — | — | 706 | 516 | — |
| IIc1sB | 19.0 | — | 55.0 | 854 | — | — | — | 491 | 516 | — |
| IIc2sB | 19.0 | — | 55.0 | — | 704 | — | — | 304 | 516 | — |
| IIc3sB | 19.0 | — | 55.0 | — | — | 1770 | — | 559 | 516 | — |
| IIc4sB | 19.0 | 10.5 | 57.0 | 428 | 451 | — | 413 | 422 | 516 | — |
| IIIa sA | 15.0 | — | 81.0 | 608 | 1280 | — | — | 775 | 494 | — |
| IIIa1sA | 15.0 | — | 82.0 | 590 | — | — | — | 392 | 494 | — |
| IIIa2sA | 15.0 | — | 83.0 | — | 1220 | — | — | 461 | 494 | — |
| IIIa3sA | 15.0 | — | 83.0 | — | — | 1600 | — | 549 | 494 | — |
| IIIa4sA | 15.0 | 7.9 | 82.0 | 246 | 568 | — | 308 | 402 | 494 | — |
| IIIb mB | 19.0 | — | 82.0 | 1025 | 1040 | — | — | 903 | 516 | — |
| IIIb1mB | 19.0 | — | 81.0 | 972 | — | — | — | 486 | 516 | — |
| IIIb2mB | 19.0 | — | 81.0 | — | 950 | — | — | 343 | 516 | — |
| IIIb3mB | 19.0 | — | 82.0 | — | — | 1580 | — | 530 | 516 | — |
| IIIb4mB | 19.0 | 10.5 | 81.0 | 466 | 480 | — | 466 | 564 | 516 | — |

**Table E1.6 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIc hR | 24.0 | — | 82.0 | 1214 | 608 | — | — | 1079 | 563 | — |
| IIIc1hR | 24.0 | — | 82.0 | 1230 | — | — | — | 724 | 563 | — |
| IIIc2hR | 24.0 | — | 81.0 | — | 600 | — | — | 255 | 563 | — |
| IIIc3hR | 24.0 | — | 82.0 | — | — | 1504 | — | 549 | 563 | — |
| IIIc4hR | 24.0 | 12.0 | 83.0 | 623 | 320 | — | 623 | 638 | 563 | — |
| IIbmA 1 | 24.0 | — | 57.0 | 580 | 1140 | — | — | 800 | 494 | — |
| IIbmA 2 | 24.0 | — | 56.0 | 560 | 1078 | — | — | 785 | 494 | — |
| IIbmA 3 | 24.0 | — | 57.0 | 598 | 1155 | — | — | 667 | 494 | — |
| IIbmB 1 | 24.0 | — | 56.0 | 616 | 1144 | — | — | 746 | 516 | — |
| IIbmB 2 | 24.0 | — | 56.0 | 616 | 1045 | — | — | 697 | 516 | — |
| IIbmB 3 | 24.0 | — | 57.0 | 570 | 1100 | — | — | 584 | 516 | — |
| IIbmR 1 | 24.0 | — | 57.0 | 467 | 792 | — | — | 598 | 563 | — |
| IIbmR 2 | 24.0 | — | 57.0 | 445 | 860 | — | — | 598 | 563 | — |
| IIbmR 3 | 24.0 | — | 58.0 | 435 | 825 | — | — | 598 | 563 | — |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ The rupture mode was not reported.

**Table E1.7** – German Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$ * (mm) | $t_2$ (mm) | $L_1$ † (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia sB | 24.3 | — | 46.0 | 490 | 2202 | — | — | 787 | 491 | w |
| Ia1sB | 24.3 | — | 46.0 | 416 | — | — | — | 287 | 491 | w |
| Ia2sB | 24.3 | — | 47.0 | — | 1837 | — | — | 700 | 491 | w and s |
| Ia3sB | 24.3 | — | 47.0 | — | — | 2181 | — | 776 | 491 | w and s |
| Ia4sB | 24.3 | 11.8 | 46.0 | 221 | 1021 | — | 217 | 363 | 491 | w |
| Ib mR | 24.5 | — | 47.0 | 446 | 1475 | — | — | 765 | 471 | w |
| Ib1mR | 24.5 | — | 46.0 | 418 | — | — | — | 289 | 471 | w |
| Ib2mR | 24.5 | — | 47.0 | — | 1507 | — | — | 553 | 471 | w |
| Ib3mR | 24.5 | — | 47.0 | — | — | 1772 | — | 606 | 471 | w |
| Ib4mR | 24.5 | 11.8 | 46.0 | 182 | 758 | — | 204 | 378 | 471 | s |
| Ic hA | 30.2 | — | 46.0 | 677 | 1543 | — | — | 687 | 491 | w |
| Ic1hA | 30.2 | — | 46.0 | 655 | — | — | — | 414 | 491 | w |
| Ic2hA | 30.2 | — | 46.0 | — | 1522 | — | — | 539 | 491 | w |
| Ic3hA | 30.2 | — | 46.0 | — | — | 1698 | — | 688 | 491 | w |
| Ic4hA | 30.2 | 15.2 | 46.0 | 345 | 869 | — | 340 | 502 | 491 | s |
| IIa hR | 30.3 | — | 56.0 | 493 | 1591 | — | — | 710 | 471 | w |
| IIa1hR | 30.3 | — | 56.0 | 500 | — | — | — | 327 | 471 | w |
| IIa2hR | 30.3 | — | 56.0 | — | 1581 | — | — | 529 | 471 | w |
| IIa3hR | 30.3 | — | 56.0 | — | — | 1825 | — | 615 | 471 | w |
| IIa4hR | 30.3 | 15.2 | 56.0 | 248 | 815 | — | 246 | 439 | 471 | w |
| IIb sA | 20.4 | — | 56.0 | 686 | 1407 | — | — | 787 | 491 | w |
| IIb1sA | 20.4 | — | 55.0 | 739 | — | — | — | 379 | 491 | w |
| IIb2sA | 20.4 | — | 55.0 | — | 1479 | — | — | 498 | 491 | w |
| IIb3sA | 20.4 | — | 56.0 | — | — | 1728 | — | 608 | 491 | w |
| IIb4sA | 20.4 | 10.1 | 55.0 | 346 | 814 | — | 365 | 442 | 491 | s |
| IIc mB | 24.5 | — | 56.0 | 948 | 1245 | — | — | 978 | 491 | s |
| IIc1mB | 24.5 | — | 56.0 | 892 | — | — | — | 561 | 491 | w |
| IIc2mB | 24.5 | — | 57.0 | — | 1087 | — | — | 452 | 491 | w |
| IIc3mB | 24.5 | — | 57.0 | — | — | 1695 | — | 645 | 491 | w |
| IIc4mB | 24.5 | 12.1 | 55.0 | 446 | 598 | — | 428 | 457 | 491 | s |
| IIIa mA | 20.5 | — | 82.0 | 857 | 1289 | — | — | 937 | 491 | w |
| IIIa1mA | 20.5 | — | 82.0 | 825 | — | — | — | 434 | 491 | w |
| IIIa2mA | 20.5 | — | 82.0 | — | 1400 | — | — | 439 | 491 | w |
| IIIa3mA | 20.5 | — | 82.0 | — | — | 1477 | — | 445 | 491 | w |
| IIIa4mA | 20.5 | 10.2 | 80.0 | 602 | 521 | — | 492 | 459 | 491 | s |
| IIIb hB | 24.4 | — | 82.0 | 1098 | 1303 | — | — | 1011 | 491 | w |
| IIIb1hB | 24.4 | — | 81.0 | 1424 | — | — | — | 731 | 491 | w |
| IIIb2hB | 24.4 | — | 82.0 | — | 1288 | — | — | 454 | 491 | w |
| IIIb3hB | 24.4 | — | 82.0 | — | — | 1587 | — | 599 | 491 | w |
| IIIb4hB | 24.4 | 11.8 | 80.0 | 593 | 689 | — | 610 | 569 | 491 | s |

**Table E1.7 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIc sR | 15.2 | — | 81.0 | 1291 | 748 | — | — | 785 | 471 | w |
| IIIc1sR | 15.2 | — | 82.0 | 1377 | — | — | — | 725 | 471 | w |
| IIIc2sR | 15.2 | — | 82.0 | — | 960 | — | — | 288 | 471 | w |
| IIIc3sR | 15.2 | — | 81.0 | — | — | 1320 | — | 445 | 471 | w |
| IIIc4sR | 15.2 | 7.8 | 81.0 | 588 | 420 | — | 310 | 419 | 471 | s |
| IIbmA 1 | 24.5 | — | 56.0 | 744 | 1497 | — | — | 835 | 491 | w |
| IIbmA 2 | 24.5 | — | 58.0 | 681 | 1448 | — | — | 846 | 491 | w |
| IIbmA 3 | 24.5 | — | 56.0 | 745 | 1523 | — | — | 807 | 491 | w |
| IIbmB 1 | 24.7 | — | 56.0 | 783 | 1564 | — | — | 914 | 491 | w and s |
| IIbmB 2 | 24.7 | — | 56.0 | 735 | 1601 | — | — | 951 | 491 | w and s |
| IIbmB 3 | 24.7 | — | 56.0 | 753 | 1606 | — | — | 912 | 491 | w and s |
| IIbmR 1 | 24.5 | — | 57.0 | 618 | 1343 | — | — | 789 | 471 | w |
| IIbmR 2 | 24.5 | — | 56.0 | 615 | 1242 | — | — | 783 | 471 | w |
| IIbmR 3 | 24.5 | — | 57.0 | 579 | 1204 | — | — | 757 | 471 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.8** – Belgian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $t_2$ (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia mA | 30.1 | — | 45.1 | 326 | 1634 | — | — | 755 | 505 | w |
| Ia1mA | 30.1 | — | 45.0 | 341 | — | — | — | 255 | 505 | w |
| Ia2mA | 30.1 | — | 45.9 | — | 1728 | — | — | 671 | 505 | w |
| Ia3mA | 30.1 | — | 45.2 | — | — | 1908 | — | 723 | 505 | w |
| Ia4mA | 30.1 | 15.5 | 45.2 | 130 | 804 | — | 172 | 387 | 505 | w |
| Ib sR | 19.2 | — | 46.2 | 348 | 1205 | — | — | 608 | 523 | s |
| Ib1sR | 19.2 | — | 46.6 | 419 | — | — | — | 243 | 523 | w |
| Ib2sR | 19.2 | — | 46.8 | — | 1249 | — | — | 538 | 523 | w |
| Ib3sR | 19.2 | — | 46.5 | — | — | 1552 | — | 569 | 523 | w |
| Ib4sR | 19.2 | 10.0 | 46.5 | 219 | 623 | — | 191 | 294 | 523 | s |
| Ic hB | 30.0 | — | 45.1 | 641 | 1405 | — | — | 944 | 554 | w |
| Ic1hB | 30.0 | — | 45.2 | 570 | — | — | — | 343 | 554 | w |
| Ic2hB | 30.0 | — | 44.7 | — | 1136 | — | — | 579 | 554 | w |
| Ic3hB | 30.0 | — | 45.3 | — | — | 1463 | — | 659 | 554 | w |
| Ic4hB | 30.0 | 15.3 | 44.3 | 326 | 516 | — | 255 | 445 | 554 | w |
| IIa hR | 30.0 | — | 54.5 | 442 | 1327 | — | — | 687 | 523 | w |
| IIa1hR | 30.0 | — | 55.0 | 447 | — | — | — | 245 | 523 | w |
| IIa2hR | 30.0 | — | 55.0 | — | 1466 | — | — | 555 | 523 | w |
| IIa3hR | 30.0 | — | 55.1 | — | — | 1531 | — | 577 | 523 | w |
| IIa4hR | 30.0 | 15.5 | 55.0 | 272 | 654 | — | 183 | 387 | 523 | w |
| IIb mB | 24.0 | — | 55.6 | 669 | 1294 | — | — | 1079 | 554 | w |
| IIb1mB | 24.0 | — | 55.8 | 613 | — | — | — | 512 | 554 | w |
| IIb2mB | 24.0 | — | 55.7 | — | 1266 | — | — | 589 | 554 | w |
| IIb3mB | 24.0 | — | 55.7 | — | — | 1623 | — | 753 | 554 | w |
| IIb4mB | 24.0 | 12.2 | 55.0 | 363 | 599 | — | 292 | 520 | 554 | s |
| IIc sA | 19.1 | — | 56.2 | 821 | 941 | — | — | 701 | 505 | s |
| IIc1sA | 19.1 | — | 55.6 | 940 | — | — | — | 569 | 505 | w |
| IIc2sA | 19.1 | — | 56.4 | — | 986 | — | — | 381 | 505 | w |
| IIc3sA | 19.1 | — | 55.1 | — | — | 1620 | — | 585 | 505 | w |
| IIc4sA | 19.1 | 10.0 | 55.0 | 460 | 503 | — | 387 | 353 | 505 | w |
| IIIa sB | 15.2 | — | 80.4 | 804 | 1151 | — | — | 844 | 554 | w |
| IIIa1sB | 15.2 | — | 80.5 | 673 | — | — | — | 536 | 554 | w |
| IIIa2sB | 15.2 | — | 79.9 | — | 1304 | — | — | 475 | 554 | w and s |
| IIIa3sB | 15.2 | — | 80.9 | — | — | 1727 | — | 538 | 554 | w and s |
| IIIa4sB | 15.2 | 8.6 | 81.5 | 353 | 588 | — | 588 | 459 | 554 | s |
| IIIb hA | 24.1 | — | 80.3 | 919 | 967 | — | — | 867 | 505 | w |
| IIIb1hA | 24.1 | — | 81.0 | 913 | — | — | — | 626 | 505 | w |
| IIIb2hA | 24.1 | — | 80.7 | — | 986 | — | — | 390 | 505 | w |
| IIIb3hA | 24.1 | — | 80.5 | — | — | 1705 | — | 626 | 505 | w |
| IIIb4hA | 24.1 | 12.4 | 80.0 | 435 | 518 | — | 478 | 677 | 505 | s |

**Table E1.8 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIc mR | 19.0 | — | 79.9 | 1321 | 702 | — | — | 940 | 523 | w |
| IIIc1mR | 19.0 | — | 80.1 | 1285 | — | — | — | 742 | 523 | w |
| IIIc2mR | 19.0 | — | 81.6 | — | 764 | — | — | 267 | 523 | w |
| IIIc3mR | 19.0 | — | 80.2 | — | — | 1598 | — | 491 | 523 | w |
| IIIc4mR | 19.0 | 10.2 | 80.0 | 560 | 384 | — | 580 | 518 | 523 | s |
| IIbmA 1 | 24.2 | — | 55.2 | 561 | 1156 | — | — | 829 | 505 | w |
| IIbmA 2 | 24.2 | — | 55.7 | 591 | 1075 | — | — | 736 | 505 | w |
| IIbmA 3 | 24.2 | — | 55.4 | 592 | 1095 | — | — | 770 | 505 | w |
| IIbmB 1 | 24.2 | — | 55.4 | 606 | 1261 | — | — | 1020 | 554 | w |
| IIbmB 2 | 24.2 | — | 54.8 | 540 | 1182 | — | — | 976 | 554 | w |
| IIbmB 3 | 24.2 | — | 56.0 | 568 | 1261 | — | — | 1010 | 554 | w |
| IIbmR 1 | 24.3 | — | 56.0 | 574 | 1137 | — | — | 893 | 523 | w |
| IIbmR 2 | 24.3 | — | 55.5 | 518 | 1118 | — | — | 785 | 523 | w |
| IIbmR 3 | 24.3 | — | 55.5 | 495 | 1204 | — | — | 834 | 523 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.9** – Netherlands' Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $t_2$ (mm) | $L_1$† (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia hA | 38.0 | — | 46.0 | 390 | 1780 | — | — | 780 | 474 | w |
| Ia1hA | 38.0 | — | 46.0 | 366 | — | — | — | 231 | 474 | w |
| Ia2hA | 38.0 | — | 46.0 | — | 1754 | — | — | 711 | 474 | w |
| Ia3hA | 38.0 | — | 46.0 | — | — | 2192 | — | 814 | 474 | w |
| Ia4hA | 38.0 | 19.0 | 45.0 | 198 | 906 | — | 158 | 441 | 474 | w |
| Ib mR | 24.0 | — | 45.0 | 464 | 1572 | — | — | 766 | 477 | w |
| Ib1mR | 24.0 | — | 45.0 | 418 | — | — | — | 251 | 477 | w |
| Ib2mR | 24.0 | — | 46.0 | — | 1284 | — | — | 603 | 477 | w |
| Ib3mR | 24.0 | — | 46.0 | — | — | 1838 | — | 700 | 477 | w |
| Ib4mR | 24.0 | 12.5 | 50.0 | 202 | 676 | — | 198 | 432 | 477 | w |
| Ic sB | 19.0 | — | 46.0 | 664 | 1422 | — | — | 775 | 559 | s |
| Ic1sB | 19.0 | — | 46.0 | 686 | — | — | — | 466 | 559 | w |
| Ic2sB | 19.0 | — | 46.0 | — | 1722 | — | — | 687 | 559 | w |
| Ic3sB | 19.0 | — | 46.0 | — | — | 1906 | — | 736 | 559 | s |
| Ic4sB | 19.0 | 10.0 | 44.0 | 355 | 722 | — | 267 | 358 | 559 | s |
| IIa sR | 19.0 | — | 56.0 | 419 | 1530 | — | — | 826 | 477 | w |
| IIa1sR | 19.0 | — | 56.0 | 490 | — | — | — | 294 | 477 | w |
| IIa2sR | 19.0 | — | 56.0 | — | 1650 | — | — | 623 | 477 | w |
| IIa3sR | 19.0 | — | 56.0 | — | — | 1762 | — | 687 | 477 | w |
| IIa4sR | 19.0 | 10.5 | 57.0 | 241 | 680 | — | 194 | 420 | 477 | s |
| IIb hB | 31.0 | — | 56.0 | 838 | 1494 | — | — | 1079 | 559 | w |
| IIb1hB | 31.0 | — | 55.0 | 736 | — | — | — | 540 | 559 | w |
| IIb2hB | 31.0 | — | 55.0 | — | 1326 | — | — | 633 | 559 | w |
| IIb3hB | 31.0 | — | 55.0 | — | — | 1900 | — | 800 | 559 | w |
| IIb4hB | 31.0 | 15.0 | 57.5 | 421 | 773 | — | 425 | 643 | 559 | s |
| IIc mA | 24.0 | — | 56.0 | 1000 | 1214 | — | — | 956 | 474 | w |
| IIc1mA | 24.0 | — | 55.0 | 972 | — | — | — | 528 | 474 | w |
| IIc2mA | 24.0 | — | 55.0 | — | 1182 | — | — | 446 | 474 | w |
| IIc3mA | 24.0 | — | 55.0 | — | — | 1868 | — | 746 | 474 | w |
| IIc4mA | 24.0 | 12.0 | 58.0 | 523 | 465 | — | 452 | 638 | 474 | s |
| IIIa mB | 19.0 | — | 82.0 | 873 | 1310 | — | — | 1099 | 559 | w and s |
| IIIa1mB | 19.0 | — | 80.0 | 817 | — | — | — | 638 | 559 | w |
| IIIa2mB | 19.0 | — | 80.0 | — | 1324 | — | — | 592 | 559 | w |
| IIIa3mB | 19.0 | — | 81.0 | — | — | 1836 | — | 785 | 559 | w |
| IIIa4mB | 19.0 | 10.5 | 78.0 | 443 | 754 | — | 339 | 579 | 559 | w |
| IIIb sA | 16.0 | — | 80.0 | 924 | 1032 | — | — | 853 | 474 | w and s |
| IIIb1sA | 16.0 | — | 81.0 | 1008 | — | — | — | 540 | 474 | w |
| IIIb2sA | 16.0 | — | 81.0 | — | 1005 | — | — | 392 | 474 | w |
| IIIb3sA | 16.0 | — | 81.0 | — | — | 1552 | — | 589 | 474 | w |
| IIIb4sA | 16.0 | 8.0 | 82.0 | 364 | 568 | — | 440 | 437 | 474 | s |

**Table E1.9 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIc hR | 24.0 | — | 82.0 | 1478 | 854 | — | — | 1177 | 477 | w |
| IIIc1hR | 24.0 | — | 81.0 | 1445 | — | — | — | 858 | 477 | w |
| IIIc2hR | 24.0 | — | 81.0 | — | 844 | — | — | 294 | 477 | w |
| IIIc3hR | 24.0 | — | 80.0 | — | — | 1712 | — | 706 | 477 | w |
| IIIc4hR | 24.0 | 12.0 | 82.0 | 687 | 392 | — | 648 | 799 | 477 | w |
| IIbmA 1 | 25.0 | — | 56.0 | 576 | 1254 | — | — | 775 | 474 | w |
| IIbmA 2 | 25.0 | — | 56.0 | 604 | 1204 | — | — | 726 | 474 | w |
| IIbmA 3 | 25.0 | — | 56.0 | 650 | 1206 | — | — | 770 | 474 | w |
| IIbmB 1 | 25.0 | — | 56.0 | 820 | 1550 | — | — | 947 | 559 | w and s |
| IIbmB 2 | 25.0 | — | 56.0 | 852 | 1660 | — | — | 947 | 559 | w and s |
| IIbmB 3 | 25.0 | — | 56.0 | 780 | 1480 | — | — | 932 | 559 | w and s |
| IIbmR 1 | 25.0 | — | 55.0 | 654 | 1216 | — | — | 726 | 477 | w |
| IIbmR 2 | 25.0 | — | 55.0 | 584 | 1172 | — | — | 701 | 477 | w |
| IIbmR 3 | 25.0 | — | 55.0 | 668 | 1270 | — | — | 736 | 477 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.10** – Canadian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $t_2$ (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia mR | 38.1 | — | 43.9 | 342 | 1507 | — | — | 832 | 580 | w |
| Ia1mR | 38.1 | — | 43.8 | 310 | — | — | — | 190 | 580 | w |
| Ia2mR | 38.1 | — | 44.5 | — | 1456 | — | — | 693 | 580 | w |
| Ia3mR | 38.1 | — | 44.5 | — | — | 1778 | — | 808 | 580 | w |
| Ib hB | 23.6 | — | 46.5 | 336 | 1299 | — | — | 990 | 562 | w |
| Ib1hB | 23.6 | — | 47.4 | 379 | — | — | — | 323 | 562 | w |
| Ib2hB | 23.6 | — | 44.4 | — | 1234 | — | — | 667 | 562 | w |
| Ib3hB | 23.6 | — | 44.6 | — | — | 1432 | — | 713 | 562 | w |
| Ic sA | 19.3 | — | 44.5 | 471 | 1174 | — | — | 749 | 486 | w |
| Ic1sA | 19.3 | — | 44.5 | 458 | — | — | — | 323 | 486 | w |
| Ic2sA | 19.3 | — | 44.5 | — | 1304 | — | — | 512 | 486 | w |
| Ic3sA | 19.3 | — | 44.5 | — | — | 1455 | — | 534 | 486 | w |
| IIa sB | 19.3 | — | 57.1 | 437 | 1213 | — | — | 913 | 562 | w |
| IIa1sB | 19.3 | — | 57.1 | 428 | — | — | — | 338 | 562 | w |
| IIa2sB | 19.3 | — | 56.1 | — | 1251 | — | — | 652 | 562 | w |
| IIa3sB | 19.3 | — | 56.1 | — | — | 1654 | — | 699 | 562 | w |
| IIb mA | 29.4 | — | 54.6 | 472 | 913 | — | — | 751 | 451 | w |
| IIb1mA | 29.4 | — | 55.2 | 471 | — | — | — | 347 | 451 | w |
| IIb2mA | 29.4 | — | 54.2 | — | 859 | — | — | 430 | 451 | w |
| IIb3mA | 29.4 | — | 56.4 | — | — | 1669 | — | 666 | 451 | w |
| IIc hR | 24.1 | — | 55.6 | 788 | 1079 | — | — | 1024 | 580 | w |
| IIc1hR | 24.1 | — | 55.4 | 870 | — | — | — | 730 | 580 | w |
| IIc2hR | 24.1 | — | 55.4 | — | 929 | — | — | 449 | 580 | w |
| IIc3hR | 24.1 | — | 56.6 | — | — | 1713 | — | 753 | 580 | w |
| IIIa hA | 19.3 | — | 81.8 | 802 | 1182 | — | — | 908 | 451 | w |
| IIIa1hA | 19.3 | — | 82.3 | 735 | — | — | — | 501 | 451 | w |
| IIIa2hA | 19.3 | — | 80.5 | — | 1173 | — | — | 427 | 451 | w |
| IIIa3hA | 19.3 | — | 80.3 | — | — | 1512 | — | 501 | 451 | w |
| IIIb sR | 14.0 | — | 79.2 | 893 | 889 | — | — | 853 | 580 | w |
| IIIb1sR | 14.0 | — | 80.8 | 812 | — | — | — | 622 | 580 | w |
| IIIb2sR | 14.0 | — | 81.0 | — | 841 | — | — | 367 | 580 | w |
| IIIb3sR | 14.0 | — | 80.0 | — | — | 1503 | — | 559 | 580 | w |
| IIIc mB | 23.6 | — | 80.0 | 1427 | 788 | — | — | 1247 | 562 | w |
| IIIc1mB | 23.6 | — | 80.3 | 1059 | — | — | — | 945 | 562 | w |
| IIIc2mB | 23.6 | — | 80.8 | — | 720 | — | — | 372 | 562 | w |
| IIIc3mB | 23.6 | — | 77.5 | — | — | 1591 | — | 684 | 562 | w |

**Table E1.10 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIbmA 1 | 24.6 | — | 57.0 | 403 | 851 | — | — | 632 | 451 | w |
| IIbmA 2 | 24.6 | — | 57.0 | 425 | 878 | — | — | 639 | 451 | w |
| IIbmB 1 | 24.4 | — | 58.2 | 588 | 1105 | — | — | 917 | 562 | w |
| IIbmB 2 | 24.4 | — | 56.0 | 538 | 1250 | — | — | 954 | 562 | w |
| IIbmR 1 | 23.6 | — | 57.1 | 427 | 1041 | — | — | 851 | 580 | w |
| IIbmR 2 | 23.6 | — | 57.1 | 450 | 969 | — | — | 854 | 580 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.11** – Swedish Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $t_2$ (mm) | $L_1$† (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia sR | 25.3 | — | 47.8 | 277 | 1610 | — | — | 675 | 508 | w |
| Ia1sR | 25.3 | — | 46.3 | 294 | — | — | — | 193 | 508 | w |
| Ia2sR | 25.3 | — | 46.0 | — | 1575 | — | — | 608 | 508 | w |
| Ia3sR | 25.3 | — | 45.7 | — | — | 1882 | — | 738 | 508 | w |
| Ib hB | 30.2 | — | 47.8 | 312 | 1068 | — | — | 736 | 506 | w |
| Ib1hB | 30.2 | — | 46.2 | 333 | — | — | — | 234 | 506 | w |
| Ib2hB | 30.2 | — | 46.9 | — | 1066 | — | — | 541 | 506 | w |
| Ib3hB | 30.2 | — | 47.4 | — | — | 1537 | — | 665 | 506 | w |
| Ic mA | 25.3 | — | 45.7 | 571 | 981 | — | — | 771 | 486 | w |
| Ic1mA | 25.3 | — | 46.0 | 535 | — | — | — | 302 | 486 | w |
| Ic2mA | 25.3 | — | 46.1 | — | 969 | — | — | 472 | 486 | w |
| Ic3mA | 25.3 | — | 46.6 | — | — | 1237 | — | 491 | 486 | w |
| IIa mB | 25.3 | — | 56.1 | 337 | 1303 | — | — | 676 | 506 | w |
| IIa1mB | 25.3 | — | 55.6 | 347 | — | — | — | 264 | 506 | w |
| IIa2mB | 25.3 | — | 56.0 | — | 1357 | — | — | 588 | 506 | w |
| IIa3mB | 25.3 | — | 56.5 | — | — | 1493 | — | 597 | 506 | w |
| IIb sA | 20.4 | — | 56.6 | 581 | 1148 | — | — | 692 | 486 | w |
| IIb1sA | 20.4 | — | 56.8 | 546 | — | — | — | 346 | 486 | w |
| IIb2sA | 20.4 | — | 56.2 | — | 1231 | — | — | 397 | 486 | w |
| IIb3sA | 20.4 | — | 58.7 | — | — | 1608 | — | 579 | 486 | w |
| IIc hR | 30.2 | — | 54.8 | 877 | 905 | — | — | 859 | 508 | w |
| IIc1hR | 30.2 | — | 55.4 | 913 | — | — | — | 525 | 508 | w |
| IIc2hR | 30.2 | — | 55.2 | — | 913 | — | — | 371 | 508 | w |
| IIc3hR | 30.2 | — | 55.9 | — | — | 1351 | — | 498 | 508 | w |
| IIIa hA | 25.4 | — | 82.0 | 590 | 1404 | — | — | 783 | 486 | w |
| IIIa1hA | 25.4 | — | 81.8 | 611 | — | — | — | 374 | 486 | w |
| IIIa2hA | 25.4 | — | 80.9 | — | 1249 | — | — | 428 | 486 | w |
| IIIa3hA | 25.4 | — | 82.6 | — | — | 1607 | — | 463 | 486 | w |
| IIIb mR | 21.5 | — | 80.3 | 866 | 973 | — | — | 894 | 508 | w |
| IIIb1mR | 21.5 | — | 80.9 | 913 | — | — | — | 542 | 508 | w |
| IIIb2mR | 21.5 | — | 79.9 | — | 1028 | — | — | 391 | 508 | w |
| IIIb3mR | 21.5 | — | 80.4 | — | — | 1611 | — | 591 | 508 | w |
| IIIc sB | 16.2 | — | 80.6 | 1192 | 782 | — | — | 727 | 506 | w |
| IIIc1sB | 16.2 | — | 80.2 | 1306 | — | — | — | 564 | 506 | w |
| IIIc2sB | 16.2 | — | 81.1 | — | 656 | — | — | 228 | 506 | w |
| IIIc3sB | 16.2 | — | 80.3 | — | — | 1649 | — | 509 | 506 | w |

**Table E1.11 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIbmA 1 | 25.2 | — | 56.2 | 599 | 1182 | — | — | 701 | 486 | w |
| IIbmA 2 | 25.2 | — | 56.3 | 608 | 1217 | — | — | 754 | 486 | w |
| IIbmA 3 | 25.2 | — | 55.8 | 571 | 1217 | — | — | 721 | 486 | w |
| IIbmB 1 | 25.2 | — | 56.2 | 579 | 1135 | — | — | 734 | 506 | w |
| IIbmB 2 | 25.2 | — | 55.8 | 592 | 1140 | — | — | 703 | 506 | w |
| IIbmB 3 | 25.2 | — | 55.7 | 567 | 1206 | — | — | 706 | 506 | w |
| IIbmR 1 | 25.4 | — | 55.7 | 503 | 1089 | — | — | 701 | 508 | w |
| IIbmR 2 | 25.4 | — | 56.0 | 515 | 1158 | — | — | 711 | 508 | w |
| IIbmR 3 | 25.4 | — | 56.4 | 518 | 1086 | — | — | 647 | 508 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

**Table E1.12** – Yugoslavian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $t_2$ (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $A_3$ (mm$^2$) | $A_4$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode‡ |
|---|---|---|---|---|---|---|---|---|---|---|
| Ia mA | 15.9 | — | 60.0 | 228 | 1244 | — | — | 491 | 491 | w |
| Ia1mA | 15.9 | — | 60.0 | 211 | — | — | — | 83 | 491 | w |
| Ia2mA | 15.9 | — | 60.0 | — | 1196 | — | — | 481 | 491 | w |
| Ia mB | 15.9 | — | 59.0 | 226 | 1206 | — | — | 585 | 549 | w |
| Ia1mB | 15.9 | — | 60.0 | 239 | — | — | — | 145 | 549 | w |
| Ia2mB | 15.9 | — | 60.0 | — | 1279 | — | — | 471 | 549 | w |
| Ib mA | 16.0 | — | 60.0 | 257 | 967 | — | — | 434 | 491 | w |
| Ib1mA | 16.0 | — | 60.0 | 250 | — | — | — | 108 | 491 | w |
| Ib2mA | 16.0 | — | 60.0 | — | 922 | — | — | 360 | 491 | w |
| Ib mB | 15.8 | — | 60.0 | 269 | 960 | — | — | 541 | 549 | w |
| Ib1mB | 15.8 | — | 60.0 | 335 | — | — | — | 180 | 549 | w |
| Ib2mB | 15.8 | — | 60.0 | — | 917 | — | — | 435 | 549 | w |
| Ic mA | 15.8 | — | 60.0 | 302 | 724 | — | — | 511 | 491 | w |
| Ic1mA | 15.8 | — | 60.0 | 328 | — | — | — | 177 | 491 | w |
| Ic2mA | 15.8 | — | 60.0 | — | 758 | — | — | 342 | 491 | w |
| Ic mB | 15.7 | — | 60.0 | 329 | 842 | — | — | >589+ | 549 | w |
| Ic1mB | 15.7 | — | 60.0 | 316 | — | — | — | 210 | 549 | w |
| Ic2mB | 15.7 | — | 60.0 | — | 887 | — | — | 408 | 549 | w |
| IIa mA | 16.2 | — | 60.0 | 430 | 1082 | — | — | 497 | 491 | w |
| IIa1mA | 16.2 | — | 60.0 | 329 | — | — | — | 180 | 491 | w |
| IIa2mA | 16.2 | — | 60.0 | — | 998 | — | — | 392 | 491 | w |
| IIa mB | 16.1 | — | 59.0 | 349 | 1002 | — | — | 563 | 549 | w |
| IIa1mB | 16.1 | — | 60.0 | 329 | — | — | — | 280 | 549 | w |
| IIa2mB | 16.1 | — | 60.0 | — | 988 | — | — | 409 | 549 | w |
| IIb mA | 16.1 | — | 60.0 | 366 | 773 | — | — | 452 | 491 | w |
| IIb1mA | 16.1 | — | 60.0 | 376 | — | — | — | 221 | 491 | w |
| IIb2mA | 16.1 | — | 60.0 | — | 782 | — | — | 274 | 491 | w |
| IIb mB | 16.1 | — | 59.0 | 418 | 882 | — | — | >589+ | 549 | w |
| IIb1mB | 16.1 | — | 60.0 | 376 | — | — | — | 300 | 549 | w |
| IIb2mB | 16.1 | — | 60.0 | — | 829 | — | — | 401 | 549 | w |
| IIc mA | 16.1 | — | 59.0 | 428 | 710 | — | — | 507 | 491 | w |
| IIc1mA | 16.1 | — | 60.0 | 479 | — | — | — | 279 | 491 | w |
| IIc2mA | 16.1 | — | 60.0 | — | 712 | — | — | 250 | 491 | w |
| IIc mB | 16.0 | — | 59.0 | 498 | 787 | — | — | >589+ | 549 | w |
| IIc1mB | 16.0 | — | 60.0 | 482 | — | — | — | 288 | 549 | w |
| IIc2mB | 16.0 | — | 60.0 | — | 825 | — | — | 362 | 549 | w |
| IIIa mA | 16.1 | — | 80.0 | 386 | 654 | — | — | 511 | 491 | w |
| IIIa1mA | 16.1 | — | 80.0 | 439 | — | — | — | 258 | 491 | w |
| IIIa2mA | 16.1 | — | 80.0 | — | 612 | — | — | 243 | 491 | w |

**Table E1.12 (cont.)**

| Specimen Designation | $t_1$ (mm) | $t_2$ (mm) | $L_1$ (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $A_3$ ($mm^2$) | $A_4$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) | Rupture Mode |
|---|---|---|---|---|---|---|---|---|---|---|
| IIIa mB | 16.0 | — | 80.0 | 386 | 695 | — | — | 563 | 549 | w |
| IIIa1mB | 16.0 | — | 80.0 | 457 | — | — | — | 290 | 549 | w |
| IIIa2mB | 16.0 | — | 80.0 | — | 630 | — | — | 271 | 549 | w |
| IIIb mA | 16.1 | — | 80.0 | 473 | 528 | — | — | 430 | 491 | w |
| IIIb1mA | 16.1 | — | 80.0 | 461 | — | — | — | 260 | 491 | w |
| IIIb2mA | 16.1 | — | 80.0 | — | 492 | — | — | 184 | 491 | w |
| IIIb mB | 16.0 | — | 80.0 | 498 | 517 | — | — | 577 | 549 | w |
| IIIb1mB | 16.0 | — | 80.0 | 469 | — | — | — | 320 | 549 | w |
| IIIb2mB | 16.0 | — | 80.0 | — | 520 | — | — | 261 | 549 | w |
| IIIc mA | 16.1 | — | 80.0 | 596 | 442 | — | — | 512 | 491 | w |
| IIIc1mA | 16.1 | — | 80.0 | 633 | — | — | — | 340 | 491 | w |
| IIIc2mA | 16.1 | — | 80.0 | — | 468 | — | — | 160 | 491 | w |
| IIIc mB | 16.0 | — | 80.0 | 644 | 491 | — | — | >589+ | 549 | w |
| IIIc1mB | 16.0 | — | 80.0 | 603 | — | — | — | 378 | 549 | w |
| IIIc2mB | 16.0 | — | 80.0 | — | 492 | — | — | 236 | 549 | w |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

+ Exceeded test machine capacity.

**Table E1.13** – Netherlands' Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) |
|---|---|---|---|---|---|---|
| Ib | 23.3 | 48.0 | 445 | 1123 | 895 | 544 |
| Ib1 | 23.3 | 46.0 | 392 | — | 235 | 544 |
| Ib2 | 23.3 | 45.0 | — | 1243 | 623 | 544 |
| Ib3 | 23.3 | 47.0 | — | 1545 | 682 | 544 |
| IIa | 23.3 | 57.0 | 398 | 1378 | 804 | 544 |
| IIa1 | 23.3 | 56.0 | 442 | — | 303 | 544 |
| IIa2 | 23.3 | 56.0 | — | 1392 | 564 | 544 |
| IIa3 | 23.3 | 56.0 | — | 1738 | 660 | 544 |
| IIb | 23.3 | 56.0 | 719 | 1235 | 814 | 544 |
| IIb1 | 23.3 | 56.0 | 734 | — | 348 | 544 |
| IIb2 | 23.3 | 55.0 | — | 1293 | 532 | 544 |
| IIb3 | 23.3 | 57.0 | — | 1726 | 674 | 544 |
| IIc | 23.3 | 57.0 | 804 | 996 | 917 | 544 |
| IIc1 | 23.3 | 56.0 | 882 | — | 523 | 544 |
| IIc2 | 23.3 | 59.0 | — | 961 | 471 | 544 |
| IIc3 | 23.3 | 56.0 | — | 1566 | 657 | 544 |
| IIIb | 23.3 | 82.0 | 1181 | 1178 | 1138 | 544 |
| IIIb1 | 23.3 | 81.0 | 1162 | — | 719 | 544 |
| IIIb2 | 23.3 | 82.0 | — | 1228 | 530 | 544 |
| IIIb3 | 23.3 | 81.0 | — | 1272 | 579 | 544 |
| II1 b | 23.3 | 56.0 | 525 | 986 | 741 | 544 |
| II2 b | 23.3 | 56.0 | 609 | 1098 | 798 | 544 |
| II3 b | 23.3 | 57.0 | 533 | 1167 | 831 | 544 |
| II4 b | 23.3 | 57.0 | 532 | 1136 | 736 | 544 |
| II5 b | 23.3 | 54.0 | 562 | 1092 | 831 | 544 |
| II6 b | 23.3 | 56.0 | 588 | 1058 | 769 | 544 |
| II7 b | 23.3 | 56.0 | 585 | 1012 | 780 | 544 |
| II8 b | 23.3 | 55.0 | 634 | 1146 | 809 | 544 |
| II b‡ | 23.3 | — | 612 | 1215 | 883 | 570 |
| II b | 23.3 | — | 566 | 1245 | 852 | 570 |
| II b | 23.3 | — | 567 | 1126 | 910 | 570 |
| II b | 23.3 | — | 532 | 1090 | 860 | 570 |
| II b | 23.3 | — | 591 | 1091 | 890 | 570 |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ This group of specimens was not used in the reliability analysis because no measured shear strength is available for the weld metal used in this group.

**Table E1.14** – German Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) |
|---|---|---|---|---|---|---|
| Ib | 20.0 | 46.0 | 277 | 1070 | 781 | 549 |
| Ib1 | 20.0 | 46.0 | 350 | — | 291 | 549 |
| Ib2 | 20.0 | 46.0 | — | 982 | 549 | 549 |
| Ib3 | 20.0 | 46.0 | — | 1330 | 594 | 549 |
| IIa | 20.0 | 56.0 | 348 | 1285 | 840 | 549 |
| IIa1 | 20.0 | 56.0 | 381 | — | 332 | 549 |
| IIa2 | 20.0 | 56.0 | — | 1278 | 623 | 549 |
| IIa3 | 20.0 | 56.0 | — | 1645 | 689 | 549 |
| IIb | 20.0 | 56.0 | 532 | 1140 | 954 | 549 |
| IIb1 | 20.0 | 56.0 | 538 | — | 409 | 549 |
| IIb2 | 20.0 | 56.0 | — | 1036 | 505 | 549 |
| IIb3 | 20.0 | 56.0 | — | 1665 | 673 | 549 |
| IIc | 20.0 | 55.0 | 935 | 880 | 1077 | 549 |
| IIc1 | 20.0 | 55.0 | 885 | — | 573 | 549 |
| IIc2 | 20.0 | 55.0 | — | 866 | 433 | 549 |
| IIc3 | 20.0 | 55.0 | — | 1700 | 685 | 549 |
| IIIb | 20.0 | 81.0 | 955 | 990 | 1148 | 549 |
| IIIb1 | 20.0 | 81.0 | 970 | — | 806 | 549 |
| IIIb2 | 20.0 | 81.0 | — | 935 | 426 | 549 |
| IIIb3 | 20.0 | 81.0 | — | 1530 | 603 | 549 |
| II1 b | 20.0 | 56.0 | 582 | 1070 | 903 | 549 |
| II2 b | 20.0 | 56.0 | 590 | 1190 | 907 | 549 |
| II3 b | 20.0 | 56.0 | 550 | 1110 | 869 | 549 |
| II4 b | 20.0 | 56.0 | 549 | 1155 | 926 | 549 |
| II5 b | 20.0 | 56.0 | 534 | 1045 | 918 | 549 |
| II6 b | 20.0 | 56.0 | 582 | 1120 | 903 | 549 |
| II7 b | 20.0 | 56.0 | 560 | 1140 | 921 | 549 |
| II8 b | 20.0 | 56.0 | 527 | 1140 | 902 | 549 |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

**Table E1.15** – Italian Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$ * (mm) | $L_1$ † (mm) | $A_1$ ($mm^2$) | $A_2$ ($mm^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) |
|---|---|---|---|---|---|---|
| Ib | 20.0 | 45.5 | 386 | 1059 | 834 | 553 |
| Ib1 | 20.0 | 45.3 | 460 | — | 277 | 553 |
| Ib2 | 20.0 | 45.0 | — | 1158 | 562 | 553 |
| Ib3 | 20.0 | 45.0 | — | 1460 | 687 | 553 |
| IIa | 20.0 | 55.6 | 382 | 1490 | 844 | 553 |
| IIa1 | 20.0 | 56.0 | 563 | — | 358 | 553 |
| IIa2 | 20.0 | 55.5 | — | 1460 | 663 | 553 |
| IIa3 | 20.0 | 55.4 | — | 1554 | 698 | 553 |
| IIb | 20.0 | 55.5 | 499 | 1145 | 827 | 553 |
| IIb1 | 20.0 | 55.5 | 572 | — | 339 | 553 |
| IIb2 | 20.0 | 55.5 | — | 1197 | 535 | 553 |
| IIb3 | 20.0 | 55.2 | — | 1702 | 740 | 553 |
| IIc | 20.0 | 55.2 | 884 | 1018 | 1064 | 553 |
| IIc1 | 20.0 | 55.5 | 932 | — | 571 | 553 |
| IIc2 | 20.0 | 55.5 | — | 990 | 495 | 553 |
| IIc3 | 20.0 | 55.5 | — | 1774 | 756 | 553 |
| IIIb | 20.0 | 80.3 | 1076 | 1149 | 1152 | 553 |
| IIIb1 | 20.0 | 81.0 | 1038 | — | 559 | 553 |
| IIIb2 | 20.0 | 80.5 | — | 966 | 461 | 553 |
| IIIb3 | 20.0 | 80.5 | — | 1546 | 640 | 553 |
| II1 b | 20.0 | 55.0 | 489 | 1168 | 776 | 553 |
| II2 b | 20.0 | 55.5 | 555 | 1175 | 820 | 553 |
| II3 b | 20.0 | 56.0 | 537 | 1146 | 811 | 553 |
| II4 b | 20.0 | 55.3 | 564 | 1279 | 878 | 553 |
| II5 b | 20.0 | 55.3 | 559 | 1281 | 882 | 553 |
| II6 b | 20.0 | 55.3 | 553 | 1224 | 845 | 553 |
| II7 b | 20.0 | 55.7 | 557 | 1284 | 876 | 553 |
| II8 b | 20.0 | 55.3 | 574 | 1105 | 843 | 553 |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

**Table E1.16** – Swedish Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | $t_1$* (mm) | $L_1$† (mm) | $A_1$ (mm$^2$) | $A_2$ (mm$^2$) | $P_u$ (kN) | $\sigma_u$ (MPa) |
|---|---|---|---|---|---|---|
| Ib | 22.5 | 44.0 | 312 | 974 | 656 | 558 |
| Ib1 | 22.5 | 44.0 | 281 | — | 228 | 558 |
| Ib2 | 22.5 | 43.0 | — | 777 | 481 | 558 |
| Ib3 | 22.5 | 45.0 | — | 1560 | 663 | 558 |
| IIa | 22.5 | 55.0 | 402 | 1243 | 761 | 558 |
| IIa1 | 22.5 | 55.0 | 389 | — | 281 | 558 |
| IIa2 | 22.5 | 54.0 | — | 1156 | 561 | 558 |
| IIa3 | 22.5 | 55.0 | — | 1451 | 702 | 558 |
| IIb | 22.5 | 55.0 | 524 | 987 | 864 | 558 |
| IIb | 22.5 | 55.0 | 582 | 1056 | 852 | 558 |
| IIb | 22.5 | 55.0 | 578 | 1041 | 793 | 558 |
| IIb1 | 22.5 | 55.0 | 540 | — | 392 | 558 |
| IIb1 | 22.5 | 55.0 | 545 | — | 398 | 558 |
| IIb1 | 22.5 | 55.0 | 583 | — | 399 | 558 |
| IIb2 | 22.5 | 54.0 | — | 1000 | 467 | 558 |
| IIb2 | 22.5 | 52.0 | — | 1077 | 483 | 558 |
| IIb2 | 22.5 | 55.0 | — | 964 | 535 | 558 |
| IIb3 | 22.5 | 54.0 | — | 1550 | 709 | 558 |
| IIb3 | 22.5 | 54.0 | — | 1472 | 681 | 558 |
| IIb3 | 22.5 | 53.0 | — | 1476 | 702 | 558 |
| IIc | 22.5 | 56.0 | 860 | 843 | 1012 | 558 |
| IIc1 | 22.5 | 55.0 | 858 | — | 618 | 558 |
| IIc2 | 22.5 | 55.0 | — | 741 | 466 | 558 |
| IIc3 | 22.5 | 55.0 | — | 1496 | 705 | 558 |
| IIIb | 22.5 | 80.0 | 795 | 968 | 1048 | 558 |
| IIIb1 | 22.5 | 81.0 | 866 | — | 710 | 558 |
| IIIb2 | 22.5 | 79.0 | — | 1009 | 463 | 558 |
| IIIb3 | 22.5 | 79.0 | — | 1658 | 657 | 558 |
| II b‡ | 22.5 | 56.0 | 600 | 1056 | 932 | 677 |
| II b | 22.5 | 55.0 | 550 | 1016 | 991 | 677 |
| II b | 22.5 | 55.0 | 451 | 1108 | 961 | 677 |
| II b | 22.5 | 56.0 | 532 | 1077 | 1010 | 677 |
| II b | 22.5 | 55.0 | 578 | 985 | 969 | 677 |

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), $L_1$ was reported as $h$.

‡ This group of specimens was not used in the reliability analysis because no measured shear strength is available for the weld metal used in this group.

**Table E1.17** – Summary of Ratio $\rho_G$ for Specimens Reported by Ligtenberg (1968)

| Nominal Throat Size (mm) | 3 | 3.5 | 4 | 4.5 | 5 | 6 | 7.5 | 8 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| Corresponding Leg Size (mm) | 4.2 | 4.9 | 5.7 | 6.4 | 7.1 | 8.5 | 10.6 | 11.3 | 14.1 |
| Sample Size | 97 | 67 | 91 | 13 | 302 | 145 | 41 | 87 | 31 |
| Mean $\rho_G$ | 1.230 | 1.121 | 1.109 | 1.071 | 1.056 | 1.039 | 0.986 | 0.997 | 0.996 |
| $V_G$ | 0.168 | 0.163 | 0.171 | 0.096 | 0.155 | 0.147 | 0.098 | 0.100 | 0.124 |

**Table E1.18** – Summary of Ratio $\rho_L$ for Specimens Reported by Ligtenberg (1968)

| | England | Japan | USA | France | Germany | Belgium | Netherlands | Canada | Sweden |
|---|---|---|---|---|---|---|---|---|---|
| Sample Size | 54 | 45 | 54 | 54 | 54 | 54 | 54 | 42 | 45 |
| Mean $\rho_L$ | 1.000 | 1.000 | 1.001 | 1.022 | 1.022 | 1.009 | 1.015 | 1.010 | 1.021 |
| $V_L$ | 0.004 | 0.002 | 0.001 | 0.014 | 0.012 | 0.011 | 0.019 | 0.022 | 0.016 |

**Table E1.19** – Analysis of British Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia sA | 681 | — | — | — | — | — | 682 | 0.999 | 773 | 0.881 | 718 | 0.949 | — | — |
| Ia1sA | 182 | — | — | — | 156 | 1.173 | — | — | — | — | — | — | — | — |
| Ia2sA | 645 | 365 | 302 | 1.206 | — | — | — | — | — | — | — | — | — | — |
| Ia3sA | 719 | 349 | 302 | 1.155 | — | — | — | — | — | — | — | — | — | — |
| Ia4sA | 342 | — | — | — | — | — | — | — | — | — | — | — | 414 | 0.827 |
| Ib mB | 579 | — | — | — | — | — | 664 | 0.872 | 742 | 0.781 | 667 | 0.868 | — | — |
| Ib1mB | 272 | — | — | — | 215 | 1.263 | — | — | — | — | — | — | — | — |
| Ib2mB | 491 | 406 | 381 | 1.065 | — | — | — | — | — | — | — | — | — | — |
| Ib3mB | 539 | 352 | 381 | 0.924 | — | — | — | — | — | — | — | — | — | — |
| Ib4mB | 318 | — | — | — | — | — | — | — | — | — | — | — | 411 | 0.773 |
| Ic hR | 712 | — | — | — | — | — | 630 | 1.131 | 688 | 1.035 | 630 | 1.131 | — | — |
| Ic1hR | 284 | — | — | — | 270 | 1.053 | — | — | — | — | — | — | — | — |
| Ic2hR | 429 | 377 | 329 | 1.146 | — | — | — | — | — | — | — | — | — | — |
| Ic3hR | 454 | 355 | 329 | 1.081 | — | — | — | — | — | — | — | — | — | — |
| Ic4hR | 437 | — | — | — | — | — | — | — | — | — | — | — | 446 | 0.980 |
| IIa hB | 726 | — | — | — | — | — | 708 | 1.026 | 790 | 0.919 | 710 | 1.022 | — | — |
| IIa1hB | 187 | — | — | — | 213 | 0.878 | — | — | — | — | — | — | — | — |
| IIa2hB | 579 | 390 | 381 | 1.024 | — | — | — | — | — | — | — | — | — | — |
| IIa3hB | 649 | 370 | 381 | 0.971 | — | — | — | — | — | — | — | — | — | — |
| IIa4hB | 363 | — | — | — | — | — | — | — | — | — | — | — | 442 | 0.822 |

**Table E1.19 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIb sR | 719 | — | — | — | — | — | 686 | 1.049 | 751 | 0.957 | 686 | 1.049 | — | — |
| IIb1sR | 303 | — | — | — | 312 | 0.973 | — | — | — | — | — | — | — | — |
| IIb2sR | 483 | 381 | 329 | 1.159 | — | — | — | — | — | — | — | — | — | — |
| IIb3sR | 590 | 345 | 329 | 1.049 | — | — | — | — | — | — | — | — | — | — |
| IIb4sR | 405 | — | — | — | — | — | — | — | — | — | — | — | 512 | 0.791 |
| IIc mA | 877 | — | — | — | — | — | 781 | 1.122 | 833 | 1.053 | 781 | 1.122 | — | — |
| IIc1mA | 507 | — | — | — | 490 | 1.036 | — | — | — | — | — | — | — | — |
| IIc2mA | 342 | 352 | 302 | 1.164 | — | — | — | — | — | — | — | — | — | — |
| IIc3mA | 645 | 379 | 302 | 1.254 | — | — | — | — | — | — | — | — | — | — |
| IIc4mA | 525 | — | — | — | — | — | — | — | — | — | — | — | 621 | 0.846 |
| IIIa mR | 837 | — | — | — | — | — | 811 | 1.031 | 883 | 0.947 | 811 | 1.031 | — | — |
| IIIa1mR | 316 | — | — | — | 345 | 0.916 | — | — | — | — | — | — | — | — |
| IIIa2mR | 437 | 315 | 329 | 0.958 | — | — | — | — | — | — | — | — | — | — |
| IIIa3mR | 507 | 302 | 329 | 0.919 | — | — | — | — | — | — | — | — | — | — |
| IIIa4mR | 928 | — | — | — | — | — | — | — | — | — | — | — | 547 | 1.698 |
| IIIb hA | 930 | — | — | — | — | — | 881 | 1.056 | 937 | 0.993 | 881 | 1.056 | — | — |
| IIIb1hA | 592 | — | — | — | 548 | 1.079 | — | — | — | — | — | — | — | — |
| IIIb2hA | 381 | 368 | 302 | 1.218 | — | — | — | — | — | — | — | — | — | — |
| IIIb3hA | 545 | 318 | 302 | 1.053 | — | — | — | — | — | — | — | — | — | — |
| IIIb4hA | 619 | — | — | — | — | — | — | — | — | — | — | — | 718 | 0.862 |

**Table E1.19 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIc sB | 991† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIc1sB | 801 | — | — | — | 780 | 1.028 | — | — | — | — | — | — | — | — |
| IIIc2sB | 276 | 404 | 381 | 1.059 | — | — | — | — | — | — | — | — | — | — |
| IIIc3sB | 619 | 372 | 381 | 0.976 | — | — | — | — | — | — | — | — | — | — |
| IIIc4sB | 432 | — | — | — | — | — | — | — | — | — | — | — | 874 | 0.494 |
| IIbmA 1 | 735 | — | — | — | — | — | 653 | 1.126 | 714 | 1.029 | 653 | 1.126 | — | — |
| IIbmA 2 | 765 | — | — | — | — | — | 686 | 1.116 | 749 | 1.021 | 686 | 1.116 | — | — |
| IIbmA 3 | 763 | — | — | — | — | — | 719 | 1.061 | 785 | 0.972 | 719 | 1.061 | — | — |
| IIbmB 1 | 851† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIbmB 2 | 939 | — | — | — | — | — | 750 | 1.252 | 821 | 1.143 | 750 | 1.252 | — | — |
| IIbmB 3 | 948 | — | — | — | — | — | 736 | 1.287 | 802 | 1.182 | 736 | 1.287 | — | — |
| IIbmR 1 | 837 | — | — | — | — | — | 716 | 1.169 | 784 | 1.068 | 716 | 1.169 | — | — |
| IIbmR 2 | 810 | — | — | — | — | — | 729 | 1.111 | 798 | 1.016 | 729 | 1.111 | — | — |
| IIbmR 3 | 645 | — | — | — | — | — | 674 | 0.958 | 735 | 0.879 | 674 | 0.958 | — | — |

† Specimen ruptured in steel plate.

**Table E1.20** – Analysis of Japanese Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia hA | 699 | — | — | — | — | — | 641 | 1.091 | 722 | 0.969 | 662 | 1.057 | — | — |
| Ia1hA | 202 | — | — | — | 168 | 1.204 | — | — | — | — | — | — | — | — |
| Ia2hA | 557 | 411 | 299 | 1.374 | — | — | — | — | — | — | — | — | — | — |
| Ia3hA | 580 | 393 | 299 | 1.314 | — | — | — | — | — | — | — | — | — | — |
| Ib sB | 718† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ib1sB | 277 | — | — | — | 227 | 1.217 | — | — | — | — | — | — | — | — |
| Ib2sB | 549 | 357 | 340 | 1.051 | — | — | — | — | — | — | — | — | — | — |
| Ib3sB | 586 | 349 | 340 | 1.027 | — | — | — | — | — | — | — | | — | — |
| Ic mR | 645 | — | — | — | — | — | 570 | 1.132 | 624 | 1.034 | 570 | 1.132 | — | — |
| Ic1mR | 262 | — | — | — | 262 | 0.999 | — | — | — | — | — | — | — | — |
| Ic2mR | 379 | 427 | 375 | 1.138 | — | — | — | — | — | — | — | — | — | — |
| Ic3mR | 439 | 445 | 375 | 1.186 | — | — | — | — | — | — | — | — | — | — |
| IIa mB | 715 | — | — | — | — | — | 710 | 1.008 | 787 | 0.909 | 710 | 1.008 | — | — |
| IIa1mB | 297 | — | — | — | 261 | 1.140 | — | — | — | — | — | — | — | — |
| IIa2mB | 502 | 332 | 340 | 0.976 | — | — | — | — | — | — | — | — | — | — |
| IIa3mB | 577 | 366 | 340 | 1.077 | — | — | — | — | — | — | — | — | — | — |
| IIb hR | 554 | — | — | — | — | — | 542 | 1.023 | 592 | 0.937 | 542 | 1.023 | — | — |
| IIb1hR | 293 | — | — | — | 274 | 1.070 | — | — | — | — | — | — | — | — |
| IIb2hR | 337 | 341 | 375 | 0.908 | — | — | — | — | — | — | — | — | — | — |
| IIb3hR | 598 | 346 | 375 | 0.922 | — | — | — | — | — | — | — | — | — | — |

**Table E1.20 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIc sA | 746 | — | — | — | — | — | 695 | 1.073 | 747 | 0.998 | 695 | 1.073 | — | — |
| IIc1sA | 418 | — | — | — | 388 | 1.076 | — | — | — | — | — | — | — | — |
| IIc2sA | 378 | 422 | 299 | 1.410 | — | — | — | — | — | — | — | — | — | — |
| IIc3sA | 369 | 379 | 299 | 1.269 | — | — | — | — | — | — | — | — | — | — |
| IIIa sR | 728 | — | — | — | — | — | 749 | 0.971 | 826 | 0.881 | 749 | 0.971 | — | — |
| IIIa1sR | 387 | — | — | — | 379 | 1.023 | — | — | — | — | — | — | — | — |
| IIIa2sR | 477 | 341 | 375 | 0.908 | — | — | — | — | — | — | — | — | — | — |
| IIIa3sR | 549 | 342 | 375 | 0.911 | — | — | — | — | — | — | — | — | — | — |
| IIIb mA | 752 | — | — | — | — | — | 711 | 1.058 | 757 | 0.994 | 757 | 0.994 | — | — |
| IIIb1mA | 553 | — | — | — | 454 | 1.220 | — | — | — | — | — | — | — | — |
| IIIb2mA | 302 | 371 | 299 | 1.241 | — | — | — | — | — | — | — | — | — | — |
| IIIb3mA | 454 | 356 | 299 | 1.190 | — | — | — | — | — | — | — | — | — | — |
| IIIc hB | 908 | — | — | — | — | — | 971 | 0.936 | 1013 | 0.897 | 1013 | 0.897 | — | — |
| IIIc1hB | 694 | — | — | — | 731 | 0.948 | — | — | — | — | — | — | — | — |
| IIIc2hB | 285 | 344 | 340 | 1.011 | — | — | — | — | — | — | — | — | — | — |
| IIIc3hB | 548 | 319 | 340 | 0.938 | — | — | — | — | — | — | — | — | — | — |

**Table E1.20 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIbmA 1 | 613 | — | — | — | — | — | 593 | 1.033 | 645 | 0.951 | 593 | 1.033 | — | — |
| IIbmA 2 | 604 | — | — | — | — | — | 582 | 1.038 | 634 | 0.954 | 582 | 1.038 | — | — |
| IIbmA 3 | 615 | — | — | — | — | — | 580 | 1.060 | 632 | 0.973 | 580 | 1.060 | — | — |
| IIbmB 1 | 730 | — | — | — | — | — | 683 | 1.069 | 747 | 0.977 | 683 | 1.069 | — | — |
| IIbmB 2 | 736 | — | — | — | — | — | 692 | 1.063 | 759 | 0.969 | 692 | 1.063 | — | — |
| IIbmB 3 | 743 | — | — | — | — | — | 721 | 1.031 | 787 | 0.943 | 721 | 1.031 | — | — |
| IIbmR 1 | 619 | — | — | — | — | — | 566 | 1.094 | 619 | 1.001 | 566 | 1.094 | — | — |
| IIbmR 2 | 606 | — | — | — | — | — | 548 | 1.106 | 600 | 1.010 | 548 | 1.106 | — | — |
| IIbmR 3 | 610 | — | — | — | — | — | 548 | 1.114 | 599 | 1.019 | 548 | 1.114 | — | — |

† Specimen ruptured in steel plate.

**Table E1.21** – Analysis of USA Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia mR | 557 | — | — | — | — | — | 551 | 1.011 | 621 | 0.897 | 569 | 0.979 | — | — |
| Ia1mR | 169 | — | — | — | 167 | 1.014 | — | — | — | — | — | — | — | — |
| Ia2mR | 490 | 343 | 316 | 1.085 | — | — | — | — | — | — | — | — | — | — |
| Ia3mR | 533 | 339 | 316 | 1.073 | — | — | — | — | — | — | — | — | — | — |
| Ia4mR | 381 | — | — | — | — | — | — | — | — | — | — | — | 349 | 1.091 |
| Ib hA | 659 | — | — | — | — | — | 546 | 1.208 | 605 | 1.089 | 546 | 1.208 | — | — |
| Ib1hA | 238 | — | — | — | 214 | 1.112 | — | — | — | — | — | — | — | — |
| Ib2hA | 511 | 448 | 304 | 1.473 | — | — | — | — | — | — | — | — | — | — |
| Ib3hA | 575 | 393 | 304 | 1.291 | — | — | — | — | — | — | — | — | — | — |
| Ib4hA | 383 | — | — | — | — | — | — | — | — | — | — | — | 372 | 1.029 |
| Ic sB | 713 | — | — | — | — | — | 754 | 0.945 | 824 | 0.865 | 754 | 0.945 | — | — |
| Ic1sB | 291 | — | — | — | 361 | 0.805 | — | — | — | — | — | — | — | — |
| Ic2sB | 499 | 495 | 365 | 1.357 | — | — | — | — | — | — | — | — | — | — |
| Ic3sB | 617 | 472 | 365 | 1.294 | — | — | — | — | — | — | — | — | — | — |
| Ic4sB | 342 | — | — | — | — | — | — | — | — | — | — | — | 521 | 0.656 |
| IIa sA | 604 | — | — | — | — | — | 582 | 1.037 | 650 | 0.928 | 586 | 1.030 | — | — |
| IIa1sA | 227 | — | — | — | 214 | 1.063 | — | — | — | — | — | — | — | — |
| IIa2sA | 395 | 361 | 304 | 1.186 | — | — | — | — | — | — | — | — | — | — |
| IIa3sA | 523 | 358 | 304 | 1.178 | — | — | — | — | — | — | — | — | — | — |
| IIa4sA | 303 | — | — | — | — | — | — | — | — | — | — | — | 386 | 0.785 |

**Table E1.21 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIb mB | 684 | — | — | — | — | — | 698 | 0.981 | 761 | 0.899 | 698 | 0.981 | — | — |
| IIb1mB | 363 | — | — | — | 384 | 0.945 | — | — | — | — | — | — | — | — |
| IIb2mB | 414 | 429 | 365 | 1.176 | — | — | — | — | — | — | — | — | — | — |
| IIb3mB | 666 | 430 | 365 | 1.176 | — | — | — | — | — | — | — | — | — | — |
| IIb4mB | 462 | — | — | — | — | — | — | — | — | — | — | — | 493 | 0.938 |
| IIc hA | 715 | — | — | — | — | — | 769 | 0.930 | 817 | 0.875 | 769 | 0.930 | — | — |
| IIc1hA | 445 | — | — | — | 527 | 0.845 | — | — | — | — | — | — | — | — |
| IIc2hA | 325 | 378 | 316 | 1.197 | — | — | — | — | — | — | — | — | — | — |
| IIc3hA | 597 | 351 | 316 | 1.111 | — | — | — | — | — | — | — | — | — | — |
| IIc4hA | 581 | — | — | — | — | — | — | — | — | — | — | — | 656 | 0.887 |
| IIIa hB | 951 | — | — | — | — | — | 839 | 1.134 | 910 | 1.045 | 839 | 1.134 | — | — |
| IIIa1hB | 543 | — | — | — | 468 | 1.160 | — | — | — | — | — | — | — | — |
| IIIa2hB | 470 | 466 | 365 | 1.276 | — | — | — | — | — | — | — | — | — | — |
| IIIa3hB | 615 | 428 | 365 | 1.171 | — | — | — | — | — | — | — | — | — | — |
| IIIa4hB | 575 | — | — | — | — | — | — | — | — | — | — | — | 634 | 0.907 |
| IIIb sR | 710 | — | — | — | — | — | 616 | 1.153 | 657 | 1.081 | 616 | 1.153 | — | — |
| IIIb1sR | 461 | — | — | — | 421 | 1.095 | — | — | — | — | — | — | — | — |
| IIIb2sR | 292 | 347 | 316 | 1.097 | — | — | — | — | — | — | — | — | — | — |
| IIIb3sR | 471 | 348 | 316 | 1.102 | — | — | — | — | — | — | — | — | — | — |
| IIIb4sR | 399 | — | — | — | — | — | — | — | — | — | — | — | 435 | 0.917 |

**Table E1.21 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIc mA | 890 | — | — | — | — | — | 980 | 0.908 | 1016 | 0.875 | 980 | 0.908 | — | — |
| IIIc1mA | 708 | — | — | — | 806 | 0.879 | — | — | — | — | — | — | — | — |
| IIIc2mA | 303 | 513 | 304 | 1.687 | — | — | — | — | — | — | — | — | — | — |
| IIIc3mA | 539 | 388 | 304 | 1.274 | — | — | — | — | — | — | — | — | — | — |
| IIIc4mA | 497 | | — | — | — | — | — | — | — | — | — | — | 636 | 0.781 |
| IIbmA 1 | 734 | — | — | — | — | — | 730 | 1.005 | 795 | 0.923 | 730 | 1.005 | — | — |
| IIbmA 2 | 774 | — | — | — | — | — | 722 | 1.071 | 789 | 0.981 | 722 | 1.071 | — | — |
| IIbmA 3 | 757 | — | — | — | — | — | 775 | 0.977 | 844 | 0.897 | 775 | 0.977 | — | — |
| IIbmB 1 | 742 | — | — | — | — | — | 721 | 1.028 | 787 | 0.942 | 721 | 1.028 | — | — |
| IIbmB 2 | 744 | — | — | — | — | — | 667 | 1.115 | 729 | 1.020 | 667 | 1.115 | — | — |
| IIbmB 3 | 726 | — | — | — | — | — | 724 | 1.003 | 789 | 0.920 | 724 | 1.003 | — | — |
| IIbmR 1 | 606 | — | — | — | — | — | 541 | 1.120 | 592 | 1.022 | 541 | 1.120 | — | — |
| IIbmR 2 | 619 | — | — | — | — | — | 503 | 1.231 | 550 | 1.125 | 503 | 1.231 | — | — |
| IIbmR 3 | 601 | — | — | — | — | — | 536 | 1.122 | 584 | 1.029 | 536 | 1.122 | — | — |

**Table E1.22** – Analysis of French Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia hB | 785 | — | — | — | — | — | 650 | 1.208 | 735 | 1.068 | 678 | 1.157 | — | — |
| Ia1hB | 155 | — | — | — | 150 | 1.035 | — | — | — | — | — | — | — | — |
| Ia2hB | 618 | 364 | 346 | 1.052 | — | — | — | — | — | — | — | — | — | — |
| Ia3hB | 697 | 338 | 346 | 0.978 | — | — | — | — | — | — | — | — | — | — |
| Ia4hB | 383 | — | — | — | — | — | — | — | — | — | — | — | 380 | 1.008 |
| IbsR | 667 | — | — | — | — | — | 480 | 1.389 | 536 | 1.244 | 482 | 1.385 | — | — |
| Ib1sR | 196 | — | — | — | 174 | 1.128 | — | — | — | — | — | — | — | — |
| Ib2sR | 500 | 439 | 377 | 1.163 | — | — | — | — | — | — | — | — | — | — |
| Ib3sR | 515 | 379 | 377 | 1.004 | — | — | — | — | — | — | — | — | — | — |
| Ib4sR | 309 | — | — | — | — | — | — | — | — | — | — | — | 330 | 0.937 |
| Ic mA | 755 | — | — | — | — | — | 690 | 1.094 | 753 | 1.003 | 690 | 1.094 | — | — |
| Ic1mA | 353 | — | — | — | 377 | 0.936 | — | — | — | — | — | — | — | — |
| Ic2mA | 451 | 427 | 331 | 1.290 | — | — | — | — | — | — | — | — | — | — |
| Ic3mA | 491 | 374 | 331 | 1.129 | — | — | — | — | — | — | — | — | — | — |
| Ic4mA | 383 | — | — | — | — | — | — | — | — | — | — | — | 501 | 0.764 |
| IIa mR | 608 | — | — | — | — | — | 598 | 1.018 | 668 | 0.910 | 602 | 1.011 | — | — |
| IIa1mR | 216 | — | — | — | 189 | 1.142 | — | — | — | — | — | — | — | — |
| IIa2mR | 491 | 361 | 377 | 0.956 | — | — | — | — | — | — | — | — | — | — |
| IIa3mR | 569 | 358 | 377 | 0.949 | — | — | — | — | — | — | — | — | — | — |
| IIa4mR | 373 | — | — | — | — | — | — | — | — | — | — | — | 417 | 0.895 |

**Table E1.22 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIb hA | 834 | — | — | — | — | — | 710 | 1.175 | 775 | 1.076 | 710 | 1.175 | — | — |
| IIb1hA | 341 | — | — | — | 327 | 1.045 | — | — | — | — | — | — | — | — |
| IIb2hA | 461 | 466 | 331 | 1.406 | — | — | — | — | — | — | — | — | — | — |
| IIb3hA | 638 | 391 | 331 | 1.181 | — | — | — | — | — | — | — | — | — | — |
| IIb4hA | 491 | — | — | — | — | — | — | — | — | — | — | — | 516 | 0.951 |
| IIc sB | 706 | — | — | — | — | — | 722 | 0.979 | 764 | 0.924 | 722 | 0.979 | — | — |
| IIc1sB | 491 | — | — | — | 458 | 1.070 | — | — | — | — | — | — | — | — |
| IIc2sB | 304 | 432 | 346 | 1.249 | — | — | — | — | — | — | — | — | — | — |
| IIc3sB | 559 | 316 | 346 | 0.914 | — | — | — | — | — | — | — | — | — | — |
| IIc4sB | 422 | — | — | — | — | — | — | — | — | — | — | — | 588 | 0.717 |
| IIIa sA | 775 | — | — | — | — | — | 793 | 0.977 | 869 | 0.892 | 793 | 0.977 | — | — |
| IIIa1sA | 392 | — | — | — | 351 | 1.118 | — | — | — | — | — | — | — | — |
| IIIa2sA | 461 | 378 | 331 | 1.141 | — | — | — | — | — | — | — | — | — | — |
| IIIa3sA | 549 | 343 | 331 | 1.036 | — | — | — | — | — | — | — | — | — | — |
| IIIa4sA | 402 | — | — | — | — | — | — | — | — | — | — | — | 521 | 0.772 |
| IIIb mB | 903 | — | — | — | — | — | 866 | 1.042 | 922 | 0.979 | 866 | 1.042 | — | — |
| IIIb1mB | 486 | — | — | — | 522 | 0.931 | — | — | — | — | — | — | — | — |
| IIIb2mB | 343 | 361 | 346 | 1.045 | — | — | — | — | — | — | — | — | — | — |
| IIIb3mB | 530 | 335 | 346 | 0.970 | — | — | — | — | — | — | — | — | — | — |
| IIIb4mB | 564 | — | — | — | — | — | — | — | — | — | — | — | 646 | 0.873 |

**Table E1.22 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIc hR | 1079 | — | — | — | — | — | 906 | 1.191 | 942 | 1.146 | 906 | 1.191 | — | — |
| IIIc1hR | 724 | — | — | — | 715 | 1.012 | — | — | — | — | — | — | — | — |
| IIIc2hR | 255 | 425 | 377 | 1.127 | — | — | — | — | — | — | — | — | — | — |
| IIIc3hR | 549 | 365 | 377 | 0.968 | — | — | — | — | — | — | — | — | — | — |
| IIIc4hR | 638 | — | — | — | — | — | — | — | — | — | — | — | 830 | 0.769 |
| IIbmA 1 | 800 | — | — | — | — | — | 729 | 1.096 | 797 | 1.003 | 729 | 1.096 | — | — |
| IIbmA 2 | 785 | — | — | — | — | — | 696 | 1.127 | 761 | 1.032 | 696 | 1.127 | — | — |
| IIbmA 3 | 667 | — | — | — | — | — | 745 | 0.895 | 814 | 0.820 | 745 | 0.895 | — | — |
| IIbmB 1 | 746 | — | — | — | — | — | 678 | 1.099 | 740 | 1.008 | 678 | 1.099 | — | — |
| IIbmB 2 | 697 | — | — | — | — | — | 648 | 1.074 | 704 | 0.989 | 648 | 1.074 | — | — |
| IIbmB 3 | 584 | — | — | — | — | — | 640 | 0.912 | 699 | 0.835 | 640 | 0.912 | — | — |
| IIbmR 1 | 598 | — | — | — | — | — | 533 | 1.123 | 579 | 1.034 | 533 | 1.123 | — | — |
| IIbmR 2 | 598 | — | — | — | — | — | 542 | 1.104 | 592 | 1.010 | 542 | 1.104 | — | — |
| IIbmR 3 | 598 | — | — | — | — | — | 525 | 1.140 | 573 | 1.045 | 525 | 1.140 | — | — |

**Table E1.23** – Analysis of German Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia sB | 787† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ia1sB | 287 | — | — | — | 235 | 1.221 | — | — | — | — | — | — | — | — |
| Ia2sB | 700 | 381 | 329 | 1.160 | — | — | — | — | — | — | — | — | — | — |
| Ia3sB | 776 | 356 | 329 | 1.083 | — | — | — | — | — | — | — | — | — | — |
| Ia4sB | 363† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ib mR | 765 | — | — | — | — | — | 647 | 1.183 | 721 | 1.061 | 647 | 1.183 | — | — |
| Ib1mR | 289 | — | — | — | 211 | 1.372 | — | — | — | — | — | — | — | — |
| Ib2mR | 553 | 367 | 315 | 1.164 | — | — | — | — | — | — | — | — | — | — |
| Ib3mR | 606 | 342 | 315 | 1.084 | — | — | — | — | — | — | — | — | — | — |
| Ib4mR | 378† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ic hA | 687 | — | — | — | — | — | 800 | 0.858 | 880 | 0.781 | 800 | 0.858 | — | — |
| Ic1hA | 414 | — | — | — | 338 | 1.226 | — | — | — | — | — | — | — | — |
| Ic2hA | 539 | 354 | 329 | 1.077 | — | — | — | — | — | — | — | — | — | — |
| Ic3hA | 688 | 405 | 329 | 1.232 | — | — | — | — | — | — | — | — | — | — |
| Ic4hA | 502† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIa hR | 710 | — | — | — | — | — | 704 | 1.009 | 784 | 0.906 | 704 | 1.009 | — | — |
| IIa1hR | 327 | — | — | — | 252 | 1.295 | — | — | — | — | — | — | — | — |
| IIa2hR | 529 | 334 | 315 | 1.060 | — | — | — | — | — | — | — | — | — | — |
| IIa3hR | 615 | 337 | 315 | 1.068 | — | — | — | — | — | — | — | — | — | — |
| IIa4hR | 439 | — | — | — | — | — | — | — | — | — | — | — | 482 | 0.909 |

**Table E1.23 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIb sA | 787 | — | — | — | — | — | 765 | 1.029 | 837 | 0.940 | 765 | 1.029 | — | — |
| IIb1sA | 379 | — | — | — | 381 | 0.994 | — | — | — | — | — | — | — | — |
| IIb2sA | 498 | 337 | 329 | 1.025 | — | — | — | — | — | — | — | — | — | — |
| IIb3sA | 608 | 352 | 329 | 1.071 | — | — | — | — | — | — | — | — | — | — |
| IIb4sA | 442† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIc mB | 978† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIc1mB | 561 | — | — | — | 505 | 1.112 | — | — | — | — | — | — | — | — |
| IIc2mB | 452 | 416 | 329 | 1.266 | — | — | — | — | — | — | — | — | — | — |
| IIc3mB | 645 | 380 | 329 | 1.157 | — | — | — | — | — | — | — | — | — | — |
| IIc4mB | 457† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIa mA | 937 | — | — | — | — | — | 819 | 1.145 | 885 | 1.059 | 819 | 1.145 | — | — |
| IIIa1mA | 434 | — | — | — | 425 | 1.019 | — | — | — | — | — | — | — | — |
| IIIa2mA | 439 | 313 | 329 | 0.953 | — | — | — | — | — | — | — | — | — | — |
| IIIa3mA | 445 | 302 | 329 | 0.918 | — | — | — | — | — | — | — | — | — | — |
| IIIa4mA | 459† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIb hB | 1011 | — | — | — | — | — | 1039 | 0.973 | 1113 | 0.909 | 1039 | 0.973 | — | — |
| IIIb1hB | 731 | — | — | — | 806 | 0.907 | — | — | — | — | — | — | — | — |
| IIIb2hB | 454 | 353 | 329 | 1.073 | — | — | — | — | — | — | — | — | — | — |
| IIIb3hB | 599 | 378 | 329 | 1.149 | — | — | — | — | — | — | — | — | — | — |
| IIIb4hB | 569† | — | — | — | — | — | — | — | — | — | — | — | — | — |

## Table E1.23 (cont.)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIc sR | 785 | — | — | — | — | — | 865 | 0.907 | 903 | 0.869 | 865 | 0.907 | — | — |
| IIIc1sR | 725 | — | — | — | 695 | 1.043 | — | — | — | — | — | — | — | — |
| IIIc2sR | 288 | 300 | 315 | 0.952 | — | — | — | — | — | — | — | — | — | — |
| IIIc3sR | 445 | 337 | 315 | 1.069 | — | — | — | — | — | — | — | — | — | — |
| IIIc4sR | 419† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIbmA 1 | 835 | — | — | — | — | — | 821 | 1.017 | 898 | 0.929 | 821 | 1.017 | — | — |
| IIbmA 2 | 846 | — | — | — | — | — | 774 | 1.092 | 849 | 0.996 | 774 | 1.092 | — | — |
| IIbmA 3 | 807 | — | — | — | — | — | 829 | 0.974 | 908 | 0.889 | 829 | 0.974 | — | — |
| IIbmB 1 | 914 | — | — | — | — | — | 945 | 0.968 | 1033 | 0.885 | 945 | 0.968 | — | — |
| IIbmB 2 | 951 | — | — | — | — | — | 929 | 1.023 | 1020 | 0.932 | 929 | 1.023 | — | — |
| IIbmB 3 | 912 | — | — | — | — | — | 941 | 0.969 | 1032 | 0.884 | 941 | 0.969 | — | — |
| IIbmR 1 | 789 | — | — | — | — | — | 696 | 1.133 | 764 | 1.033 | 696 | 1.133 | — | — |
| IIbmR 2 | 783 | — | — | — | — | — | 666 | 1.176 | 728 | 1.075 | 666 | 1.176 | — | — |
| IIbmR 3 | 757 | — | — | — | — | — | 636 | 1.190 | 697 | 1.086 | 636 | 1.190 | — | — |

† Specimen ruptured in steel plate.

**Table E1.24** – Analysis of Belgian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia mA | 755 | — | — | — | — | — | 713 | 1.060 | 806 | 0.937 | 744 | 1.015 | — | — |
| Ia1mA | 255 | — | — | — | 194 | 1.314 | — | — | — | — | — | — | — | — |
| Ia2mA | 671 | 388 | 338 | 1.148 | — | — | — | — | — | — | — | — | — | — |
| Ia3mA | 723 | 379 | 338 | 1.120 | — | — | — | — | — | — | — | — | — | — |
| Ia4mA | 387 | — | — | — | — | — | — | — | — | — | — | — | 431 | 0.896 |
| Ib sR | 608† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ib1sR | 243 | — | — | — | 231 | 1.052 | — | — | — | — | — | — | — | — |
| Ib2sR | 538 | 430 | 350 | 1.229 | — | — | — | — | — | — | — | — | — | — |
| Ib3sR | 569 | 367 | 350 | 1.047 | — | — | — | — | — | — | — | — | — | — |
| Ib4sR | 294† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ic hB | 944 | — | — | — | — | — | 921 | 1.024 | 1012 | 0.933 | 921 | 1.024 | — | — |
| Ic1hB | 343 | — | — | — | 365 | 0.939 | — | — | — | — | — | — | — | — |
| Ic2hB | 579 | 509 | 371 | 1.372 | — | — | — | — | — | — | — | — | — | — |
| Ic3hB | 659 | 451 | 371 | 1.214 | — | — | — | — | — | — | — | — | — | — |
| Ic4hB | 445 | — | — | — | — | — | — | — | — | — | — | — | 560 | 0.795 |
| IIa hR | 687 | — | — | — | — | — | 659 | 1.042 | 733 | 0.937 | 659 | 1.042 | — | — |
| IIa1hR | 245 | — | — | — | 247 | 0.994 | — | — | — | — | — | — | — | — |
| IIa2hR | 555 | 379 | 350 | 1.082 | — | — | — | — | — | — | — | — | — | — |
| IIa3hR | 577 | 377 | 350 | 1.076 | — | — | — | — | — | — | — | — | — | — |
| IIa4hR | 387 | — | — | — | — | — | — | — | — | — | — | — | 456 | 0.848 |

## Table E1.24 (cont.)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIb mB | 1079 | — | — | — | — | — | 899 | 1.200 | 982 | 1.099 | 899 | 1.200 | — | — |
| IIb1mB | 512 | — | — | — | 393 | 1.303 | — | — | — | — | — | — | — | — |
| IIb2mB | 589 | 465 | 371 | 1.252 | — | — | — | — | — | — | — | — | — | — |
| IIb3mB | 753 | 464 | 371 | 1.250 | — | — | — | — | — | — | — | — | — | — |
| IIb4mB | 520† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIc sA | 701† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIc1sA | 569 | — | — | — | 535 | 1.063 | — | — | — | — | — | — | — | — |
| IIc2sA | 381 | 386 | 338 | 1.141 | — | — | — | — | — | — | — | — | — | — |
| IIc3sA | 585 | 361 | 338 | 1.067 | — | — | — | — | — | — | — | — | — | — |
| IIc4sA | 353† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIa sB | 844 | — | — | — | — | — | 934 | 0.904 | 1007 | 0.837 | 934 | 0.904 | — | — |
| IIIa1sB | 536 | — | — | — | 431 | 1.241 | — | — | — | — | — | — | — | — |
| IIIa2sB | 475 | 364 | 371 | 0.981 | — | — | — | — | — | — | — | — | — | — |
| IIIa3sB | 538 | 311 | 371 | 0.839 | — | — | — | — | — | — | — | — | — | — |
| IIIa4sB | 459† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIb hA | 867 | — | — | — | — | — | 835 | 1.038 | 890 | 0.974 | 835 | 1.038 | — | — |
| IIIb1hA | 626 | — | — | — | 520 | 1.204 | — | — | — | — | — | — | — | — |
| IIIb2hA | 390 | 396 | 338 | 1.171 | — | — | — | — | — | — | — | — | — | — |
| IIIb3hA | 626 | 367 | 338 | 1.085 | — | — | — | — | — | — | — | — | — | — |
| IIIb4hA | 677† | — | — | — | — | — | — | — | — | — | — | — | — | — |

**Table E1.24 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIc mR | 940 | — | — | — | — | — | 949 | 0.990 | 988 | 0.951 | 949 | 0.990 | — | — |
| IIIc1mR | 742 | — | — | — | 710 | 1.045 | — | — | — | — | — | — | — | — |
| IIIc2mR | 267 | 349 | 350 | 0.998 | — | — | — | — | — | — | — | — | — | — |
| IIIc3mR | 491 | 307 | 350 | 0.877 | — | — | — | — | — | — | — | — | — | — |
| IIIc4mR | 518† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIbmA 1 | 829 | — | — | — | — | — | 692 | 1.197 | 758 | 1.093 | 692 | 1.197 | — | — |
| IIbmA 2 | 736 | — | — | — | — | — | 683 | 1.077 | 744 | 0.988 | 683 | 1.077 | — | — |
| IIbmA 3 | 770 | — | — | — | — | — | 690 | 1.116 | 753 | 1.023 | 690 | 1.116 | — | — |
| IIbmB 1 | 1020 | — | — | — | — | — | 847 | 1.205 | 928 | 1.100 | 847 | 1.205 | — | — |
| IIbmB 2 | 976 | — | — | — | — | — | 776 | 1.258 | 851 | 1.146 | 776 | 1.258 | — | — |
| IIbmB 3 | 1010 | — | — | — | — | — | 822 | 1.229 | 903 | 1.119 | 822 | 1.229 | — | — |
| IIbmR 1 | 893 | — | — | — | — | — | 673 | 1.327 | 736 | 1.214 | 673 | 1.327 | — | — |
| IIbmR 2 | 785 | — | — | — | — | — | 636 | 1.234 | 698 | 1.125 | 636 | 1.234 | — | — |
| IIbmR 3 | 834 | — | — | — | — | — | 650 | 1.283 | 717 | 1.164 | 650 | 1.283 | — | — |

† Specimen ruptured in steel plate.

**Table E1.25** – Analysis of Netherlands' Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia hA | 780 | — | — | — | — | — | 812 | 0.960 | 916 | 0.852 | 840 | 0.928 | — | — |
| Ia1hA | 231 | — | — | — | 213 | 1.084 | — | — | — | — | — | — | — | — |
| Ia2hA | 711 | 405 | 317 | 1.277 | — | — | — | — | — | — | — | — | — | — |
| Ia3hA | 814 | 371 | 317 | 1.170 | — | — | — | — | — | — | — | — | — | — |
| Ia4hA | 441 | — | — | — | — | — | — | — | — | — | — | — | 505 | 0.874 |
| Ib mR | 766 | — | — | — | — | — | 806 | 0.951 | 899 | 0.852 | 807 | 0.949 | — | — |
| Ib1mR | 251 | — | — | — | 249 | 1.010 | — | — | — | — | — | — | — | — |
| Ib2mR | 603 | 470 | 319 | 1.471 | — | — | — | — | — | — | — | — | — | — |
| Ib3mR | 700 | 381 | 319 | 1.193 | — | — | — | — | — | — | — | — | — | — |
| Ib4mR | 432 | — | — | — | — | — | — | — | — | — | — | — | 466 | 0.927 |
| Ic sB | 775† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ic1sB | 466 | — | — | — | 439 | 1.063 | — | — | — | — | — | — | — | — |
| Ic2sB | 687 | 399 | 375 | 1.064 | — | — | — | — | — | — | — | — | — | — |
| Ic3sB | 736† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ic4sB | 358† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIa sR | 826 | — | — | — | — | — | 765 | 1.080 | 856 | 0.965 | 773 | 1.069 | — | — |
| IIa1sR | 294 | — | — | — | 291 | 1.010 | — | — | — | — | — | — | — | — |
| IIa2sR | 623 | 378 | 319 | 1.182 | — | — | — | — | — | — | — | — | — | — |
| IIa3sR | 687 | 390 | 319 | 1.220 | — | — | — | — | — | — | — | — | — | — |
| IIa4sR | 420† | — | — | — | — | — | — | — | — | — | — | — | — | — |

**Table E1.25 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIb hB | 1079 | — | — | — | — | — | 1077 | 1.002 | 1172 | 0.920 | 1077 | 1.002 | — | — |
| IIb1hB | 540 | — | — | — | 470 | 1.147 | — | — | — | — | — | — | — | — |
| IIb2hB | 633 | 477 | 375 | 1.274 | — | — | — | — | — | — | — | — | — | — |
| IIb3hB | 800 | 421 | 375 | 1.123 | — | — | — | — | — | — | — | — | — | — |
| IIb4hB | 643† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIc mA | 956 | — | — | — | — | — | 980 | 0.976 | 1051 | 0.910 | 980 | 0.976 | — | — |
| IIc1mA | 528 | — | — | — | 565 | 0.935 | — | — | — | — | — | — | — | — |
| IIc2mA | 446 | 378 | 317 | 1.190 | — | — | — | — | — | — | — | — | — | — |
| IIc3mA | 746 | 399 | 317 | 1.257 | — | — | — | — | — | — | — | — | — | — |
| IIc4mA | 638† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIa mB | 1099 | — | — | — | — | — | 1033 | 1.064 | 1116 | 0.984 | 1033 | 1.064 | — | — |
| IIIa1mB | 638 | — | — | — | 522 | 1.221 | — | — | — | — | — | — | — | — |
| IIIa2mB | 592 | 447 | 375 | 1.193 | — | — | — | — | — | — | — | — | — | — |
| IIIa3mB | 785 | 427 | 375 | 1.141 | — | — | — | — | — | — | — | — | — | — |
| IIIa4mB | 579† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIb sA | 853 | — | — | — | — | — | 876 | 0.974 | 936 | 0.912 | 876 | 0.974 | — | — |
| IIIb1sA | 540 | — | — | — | 585 | 0.922 | — | — | — | — | — | — | — | — |
| IIIb2sA | 392 | 390 | 317 | 1.230 | — | — | — | — | — | — | — | — | — | — |
| IIIb3sA | 589 | 379 | 317 | 1.195 | — | — | — | — | — | — | — | — | — | — |
| IIIb4sA | 437† | — | — | — | — | — | — | — | — | — | — | — | — | — |

**Table E1.25 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIc hR | 1177 | — | — | — | — | — | 1167 | 1.009 | 1218 | 0.967 | 1167 | 1.009 | — | — |
| IIIc1hR | 858 | — | — | — | 860 | 0.999 | — | — | — | — | — | — | — | — |
| IIIc2hR | 294 | 349 | 319 | 1.092 | — | — | — | — | — | — | — | — | — | — |
| IIIc3hR | 706 | 413 | 319 | 1.292 | — | — | — | — | — | — | — | — | — | — |
| IIIc4hR | 799 | | | | — | — | — | — | — | — | — | — | 926 | 0.862 |
| IIbmA 1 | 775 | — | — | — | — | — | 747 | 1.037 | 820 | 0.945 | 747 | 1.037 | — | — |
| IIbmA 2 | 726 | — | — | — | — | — | 747 | 0.972 | 817 | 0.888 | 747 | 0.972 | — | — |
| IIbmA 3 | 770 | — | — | — | — | — | 775 | 0.994 | 845 | 0.912 | 775 | 0.994 | — | — |
| IIbmB 1 | 947 | — | — | — | — | — | 1086 | 0.872 | 1185 | 0.799 | 1086 | 0.872 | — | — |
| IIbmB 2 | 947 | — | — | — | — | — | 1146 | 0.826 | 1252 | 0.756 | 1146 | 0.826 | — | — |
| IIbmB 3 | 932 | — | — | — | — | — | 1035 | 0.901 | 1129 | 0.825 | 1035 | 0.901 | — | — |
| IIbmR 1 | 726 | — | — | — | — | — | 799 | 0.909 | 871 | 0.833 | 799 | 0.909 | — | — |
| IIbmR 2 | 701 | — | — | — | — | — | 742 | 0.945 | 812 | 0.864 | 742 | 0.945 | — | — |
| IIbmR 3 | 736 | — | — | — | — | — | 825 | 0.891 | 901 | 0.817 | 825 | 0.891 | — | — |

† Specimen ruptured in steel plate.

**Table E1.26** – Analysis of Canadian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia mR | 832 | — | — | — | — | — | 796 | 1.046 | 896 | 0.929 | 820 | 1.015 | — | — |
| Ia1mR | 190 | — | — | — | 206 | 0.921 | — | — | — | — | — | — | — | — |
| Ia2mR | 693 | 476 | 388 | 1.227 | — | — | — | — | — | — | — | — | — | — |
| Ia3mR | 808 | 454 | 388 | 1.170 | — | — | — | — | — | — | — | — | — | — |
| Ib hB | 990 | — | — | — | — | — | 785 | 1.262 | 880 | 1.125 | 798 | 1.241 | — | — |
| Ib1hB | 323 | — | — | — | 277 | 1.166 | — | — | — | — | — | — | — | — |
| Ib2hB | 667 | 541 | 377 | 1.435 | — | — | — | — | — | — | — | — | — | — |
| Ib3hB | 713 | 498 | 377 | 1.321 | — | — | — | — | — | — | — | — | — | — |
| Ic sA | 749 | — | — | — | — | — | 669 | 1.120 | 738 | 1.015 | 669 | 1.120 | — | — |
| Ic1sA | 323 | — | — | — | 270 | 1.199 | — | — | — | — | — | — | — | — |
| Ic2sA | 512 | 392 | 326 | 1.205 | — | — | — | — | — | — | — | — | — | — |
| Ic3sA | 534 | 367 | 326 | 1.126 | — | — | — | — | — | — | — | — | — | — |
| IIa sB | 913 | — | — | — | — | — | 823 | 1.109 | 912 | 1.001 | 823 | 1.109 | — | — |
| IIa1sB | 338 | — | — | — | 313 | 1.079 | — | — | — | — | — | — | — | — |
| IIa2sB | 652 | 522 | 377 | 1.384 | — | — | — | — | — | — | — | — | — | — |
| IIa3sB | 699 | 422 | 377 | 1.121 | — | — | — | — | — | — | — | — | — | — |
| IIb mA | 751 | — | — | — | — | — | 582 | 1.290 | 636 | 1.181 | 582 | 1.290 | — | — |
| IIb1mA | 347 | — | — | — | 277 | 1.252 | — | — | — | — | — | — | — | — |
| IIb2mA | 430 | 501 | 302 | 1.659 | — | — | — | — | — | — | — | — | — | — |
| IIb3mA | 666 | 399 | 302 | 1.322 | — | — | — | — | — | — | — | — | — | — |

**Table E1.26 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIc hR | 1024 | — | — | — | — | — | 931 | 1.100 | 1003 | 1.021 | 931 | 1.100 | — | — |
| IIc1hR | 730 | — | — | — | 579 | 1.261 | — | — | — | — | — | — | — | — |
| IIc2hR | 449 | 484 | 388 | 1.245 | — | — | — | — | — | — | — | — | — | — |
| IIc3hR | 753 | 439 | 388 | 1.131 | — | — | — | — | — | — | — | — | — | — |
| IIIa hA | 908 | — | — | — | — | — | 866 | 1.048 | 936 | 0.970 | 866 | 1.048 | — | — |
| IIIa1hA | 501 | — | — | — | 433 | 1.158 | — | — | — | — | — | — | — | — |
| IIIa2hA | 427 | 364 | 302 | 1.205 | — | — | — | — | — | — | — | — | — | — |
| IIIa3hA | 501 | 332 | 302 | 1.098 | — | — | — | — | — | — | — | — | — | — |
| IIIb sR | 853 | — | — | — | — | — | 930 | 0.917 | 989 | 0.862 | 930 | 0.917 | — | — |
| IIIb1sR | 622 | — | — | — | 540 | 1.151 | — | — | — | — | — | — | — | — |
| IIIb2sR | 367 | 436 | 388 | 1.123 | — | — | — | — | — | — | — | — | — | — |
| IIIb3sR | 559 | 372 | 388 | 0.959 | — | — | — | — | — | — | — | — | — | — |
| IIIc mB | 1247 | — | — | — | — | — | 1372 | 0.909 | 1429 | 0.873 | 1372 | 0.909 | — | — |
| IIIc1mB | 945 | — | — | — | 775 | 1.219 | — | — | — | — | — | — | — | — |
| IIIc2mB | 372 | 516 | 377 | 1.370 | — | — | — | — | — | — | — | — | — | — |
| IIIc3mB | 684 | 430 | 377 | 1.141 | — | — | — | — | — | — | — | — | — | — |
| IIbmA 1 | 632 | — | — | — | — | — | 521 | 1.212 | 571 | 1.106 | 521 | 1.212 | — | — |
| IIbmA 2 | 639 | — | — | — | — | — | 543 | 1.176 | 595 | 1.074 | 543 | 1.176 | — | — |
| IIbmB 1 | 917 | — | — | — | — | — | 889 | 1.031 | 970 | 0.945 | 889 | 1.031 | — | — |
| IIbmB 2 | 954 | — | — | — | — | — | 913 | 1.046 | 1004 | 0.950 | 913 | 1.046 | — | — |
| IIbmR 1 | 851 | — | — | — | — | — | 677 | 1.258 | 746 | 1.141 | 677 | 1.258 | — | — |
| IIbmR 2 | 854 | — | — | — | — | — | 665 | 1.284 | 729 | 1.171 | 665 | 1.284 | — | — |

**Table E1.27** – Analysis of Swedish Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia sR | 675 | — | — | — | — | — | 684 | 0.987 | 777 | 0.869 | 724 | 0.933 | — | — |
| Ia1sR | 193 | — | — | — | 169 | 1.143 | — | — | — | — | — | — | — | — |
| Ia2sR | 608 | 386 | 340 | 1.135 | — | — | — | — | — | — | — | — | — | — |
| Ia3sR | 738 | 392 | 340 | 1.152 | — | — | — | — | — | — | — | — | — | — |
| Ib hB | 736 | — | — | — | — | — | 557 | 1.321 | 622 | 1.183 | 559 | 1.317 | — | — |
| Ib1hB | 234 | — | — | — | 202 | 1.160 | — | — | — | — | — | — | — | — |
| Ib2hB | 541 | 507 | 339 | 1.495 | — | — | — | — | — | — | — | — | — | — |
| Ib3hB | 665 | 433 | 339 | 1.276 | — | — | — | — | — | — | — | — | — | — |
| Ic mA | 771 | — | — | — | — | — | 619 | 1.245 | 673 | 1.146 | 619 | 1.245 | — | — |
| Ic1mA | 302 | — | — | — | 294 | 1.028 | — | — | — | — | — | — | — | — |
| Ic2mA | 472 | 487 | 325 | 1.497 | — | — | — | — | — | — | — | — | — | — |
| Ic3mA | 491 | 397 | 325 | 1.221 | — | — | — | — | — | — | — | — | — | — |
| IIa mB | 676 | — | — | — | — | — | 653 | 1.035 | 732 | 0.923 | 664 | 1.018 | — | — |
| IIa1mB | 264 | — | — | — | 211 | 1.253 | — | — | — | — | — | — | — | — |
| IIa2mB | 588 | 433 | 339 | 1.277 | — | — | — | — | — | — | — | — | — | — |
| IIa3mB | 597 | 400 | 339 | 1.180 | — | — | — | — | — | — | — | — | — | — |
| IIb sA | 692 | — | — | — | — | — | 677 | 1.022 | 740 | 0.935 | 677 | 1.022 | — | — |
| IIb1sA | 346 | — | — | — | 300 | 1.154 | — | — | — | — | — | — | — | — |
| IIb2sA | 397 | 323 | 325 | 0.992 | — | — | — | — | — | — | — | — | — | — |
| IIb3sA | 579 | 360 | 325 | 1.106 | — | — | — | — | — | — | — | — | — | — |

**Table E1.27 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIc hR | 859 | — | — | — | — | — | 799 | 1.075 | 851 | 1.009 | 799 | 1.075 | — | — |
| IIc1hR | 525 | — | — | — | 525 | 1.000 | — | — | — | — | — | — | — | — |
| IIc2hR | 371 | 406 | 340 | 1.194 | — | — | — | — | — | — | — | — | — | — |
| IIc3hR | 498 | 369 | 340 | 1.084 | — | — | — | — | — | — | — | — | — | — |
| IIIa hA | 783 | — | — | — | — | — | 761 | 1.028 | 838 | 0.934 | 761 | 1.028 | — | — |
| IIIa1hA | 374 | — | — | — | 336 | 1.113 | — | — | — | — | — | — | — | — |
| IIIa2hA | 428 | 342 | 325 | 1.053 | — | — | — | — | — | — | — | — | — | — |
| IIIa3hA | 463 | 288 | 325 | 0.886 | — | — | — | — | — | — | — | — | — | — |
| IIIb mR | 894 | — | — | — | — | — | 815 | 1.096 | 871 | 1.026 | 815 | 1.096 | — | — |
| IIIb1mR | 542 | — | — | — | 525 | 1.031 | — | — | — | — | — | — | — | — |
| IIIb2mR | 391 | 381 | 340 | 1.119 | — | — | — | — | — | — | — | — | — | — |
| IIIb3mR | 591 | 367 | 340 | 1.078 | — | — | — | — | — | — | — | — | — | — |
| IIIc sB | 727 | — | — | — | — | — | 993 | 0.732 | 1040 | 0.699 | 993 | 0.732 | — | — |
| IIIc1sB | 564 | — | — | — | 793 | 0.711 | — | — | — | — | — | — | — | — |
| IIIc2sB | 228 | 347 | 339 | 1.023 | — | — | — | — | — | — | — | — | — | — |
| IIIc3sB | 509 | 309 | 339 | 0.910 | — | — | — | — | — | — | — | — | — | — |

**Table E1.27 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIbmA 1 | 701 | — | — | — | — | — | 697 | 1.006 | 762 | 0.920 | 697 | 1.006 | — | — |
| IIbmA 2 | 754 | — | — | — | — | — | 713 | 1.058 | 780 | 0.967 | 713 | 1.058 | — | — |
| IIbmA 3 | 721 | — | — | — | — | — | 693 | 1.041 | 759 | 0.949 | 693 | 1.041 | — | — |
| IIbmB 1 | 734 | — | — | — | — | — | 742 | 0.989 | 811 | 0.905 | 742 | 0.989 | — | — |
| IIbmB 2 | 703 | — | — | — | — | — | 752 | 0.936 | 821 | 0.857 | 752 | 0.936 | — | — |
| IIbmB 3 | 706 | — | — | — | — | — | 759 | 0.930 | 832 | 0.849 | 759 | 0.930 | — | — |
| IIbmR 1 | 701 | — | — | — | — | — | 644 | 1.089 | 707 | 0.992 | 644 | 1.089 | — | — |
| IIbmR 2 | 711 | — | — | — | — | — | 674 | 1.056 | 740 | 0.961 | 674 | 1.056 | — | — |
| IIbmR 3 | 647 | — | — | — | — | — | 652 | 0.993 | 714 | 0.906 | 652 | 0.993 | — | — |

**Table E1.28** – Analysis of Yugoslavian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ia mA | 491 | — | — | — | — | — | 537 | 0.913 | 609 | 0.806 | 565 | 0.868 | — | — |
| Ia1mA | 83 | — | — | — | 121 | 0.686 | — | — | — | — | — | — | — | — |
| Ia2mA | 481 | 402 | 329 | 1.224 | — | — | — | — | — | — | — | — | — | — |
| Ia mB | 585 | — | — | — | — | — | 614 | 0.952 | 695 | 0.841 | 644 | 0.907 | — | — |
| Ia1mB | 145 | — | — | — | 161 | 0.900 | — | — | — | — | — | — | — | — |
| Ia2mB | 471 | 369 | 368 | 1.001 | — | — | — | — | — | — | — | — | — | — |
| Ib mA | 434 | — | — | — | — | — | 463 | 0.936 | 519 | 0.835 | 470 | 0.923 | — | — |
| Ib1mA | 108 | — | — | — | 144 | 0.750 | — | — | — | — | — | — | — | — |
| Ib2mA | 360 | 390 | 329 | 1.188 | — | — | — | — | — | — | — | — | — | — |
| Ib mB | 541 | — | — | — | — | — | 549 | 0.986 | 614 | 0.882 | 553 | 0.978 | — | — |
| Ib1mB | 180 | — | — | — | 226 | 0.794 | — | — | — | — | — | — | — | — |
| Ib2mB | 435 | 474 | 368 | 1.288 | — | — | — | — | — | — | — | — | — | — |
| Ic mA | 511 | — | — | — | — | — | 410 | 1.246 | 452 | 1.131 | 410 | 1.246 | — | — |
| Ic1mA | 177 | — | — | — | 189 | 0.935 | — | — | — | — | — | — | — | — |
| Ic2mA | 342 | 452 | 329 | 1.374 | — | — | — | — | — | — | — | — | — | — |
| Ic mB | >589 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Ic1mB | 210 | — | — | — | 213 | 0.984 | — | — | — | — | — | — | — | — |
| Ic2mB | 408 | 460 | 368 | 1.250 | — | — | — | — | — | — | — | — | — | — |
| IIa mA | 497 | — | — | — | — | — | 601 | 0.828 | 663 | 0.750 | 601 | 0.828 | — | — |
| IIa1mA | 180 | — | — | — | 189 | 0.948 | — | — | — | — | — | — | — | — |
| IIa2mA | 392 | 393 | 329 | 1.196 | — | — | — | — | — | — | — | — | — | — |

**Table E1.28 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIa mB | 563 | — | — | — | — | — | 619 | 0.910 | 687 | 0.820 | 619 | 0.910 | — | — |
| IIa1mB | 280 | — | — | — | 222 | 1.259 | — | — | — | — | — | — | — | — |
| IIa2mB | 409 | 414 | 368 | 1.125 | — | — | — | — | — | — | — | — | — | — |
| IIb mA | 452 | — | — | — | — | — | 463 | 0.977 | 507 | 0.891 | 463 | 0.977 | — | — |
| IIb1mA | 221 | — | — | — | 216 | 1.020 | — | — | — | — | — | — | — | — |
| IIb2mA | 274 | 350 | 329 | 1.065 | — | — | — | — | — | — | — | — | — | — |
| IIb mB | >589† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIb1mB | 300 | — | — | — | 254 | 1.183 | — | — | — | — | — | — | — | — |
| IIb2mB | 401 | 484 | 368 | 1.315 | — | — | — | — | — | — | — | — | — | — |
| IIc mA | 507 | — | — | — | — | — | 478 | 1.061 | 519 | 0.977 | 478 | 1.061 | — | — |
| IIc1mA | 279 | — | — | — | 276 | 1.012 | — | — | — | — | — | — | — | — |
| IIc2mA | 250 | 351 | 329 | 1.069 | — | — | — | — | — | — | — | — | — | — |
| IIc mB | >589† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIc1mB | 288 | — | — | — | 325 | 0.886 | — | — | — | — | — | — | — | — |
| IIc2mB | 362 | 439 | 368 | 1.192 | — | — | — | — | — | — | — | — | — | — |
| IIIa mA | 511 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIa1mA | 258 | — | — | — | 253 | 1.021 | — | — | — | — | — | — | — | — |
| IIIa2mA | 243 | 398 | 329 | 1.210 | — | — | — | — | — | — | — | — | — | — |
| IIIa mB | 563 | — | — | — | — | — | 526 | 1.070 | 573 | 0.982 | 526 | 1.070 | — | — |
| IIIa1mB | 290 | — | — | — | 309 | 0.941 | — | — | — | — | — | — | — | — |
| IIIa2mB | 271 | 430 | 368 | 1.168 | — | — | — | — | — | — | — | — | — | — |

**Table E1.28 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | Equation 4.9 | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIIb mA | 430 | — | — | — | — | — | 445 | 0.967 | 475 | 0.905 | 445 | 0.967 | — | — |
| IIIb1mA | 260 | — | — | — | 265 | 0.980 | — | — | — | — | — | — | — | — |
| IIIb2mA | 184 | 375 | 329 | 1.141 | — | — | — | — | — | — | — | — | — | — |
| IIIb mB | 577 | — | — | — | — | — | 534 | 1.080 | 569 | 1.014 | 534 | 1.080 | — | — |
| IIIb1mB | 320 | — | — | — | 317 | 1.010 | — | — | — | — | — | — | — | — |
| IIIb2mB | 261 | 502 | 368 | 1.363 | — | — | — | — | — | — | — | — | — | — |
| IIIc mA | 512 | — | — | — | — | — | 487 | 1.051 | 513 | 0.999 | 487 | 1.051 | — | — |
| IIIc1mA | 340 | — | — | — | 364 | 0.934 | — | — | — | — | — | — | — | — |
| IIIc2mA | 160 | 343 | 329 | 1.043 | — | — | — | — | — | — | — | — | — | — |
| IIIc mB | >589† | — | — | — | — | — | — | — | — | — | — | — | — | — |
| IIIc1mB | 378 | — | — | — | 407 | 0.928 | — | — | — | — | — | — | — | — |
| IIIc2mB | 236 | 480 | 368 | 1.303 | — | — | — | — | — | — | — | — | — | — |

† Exceeded test machine capacity.

**Table E1.29** – Analysis of Netherlands' Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ib | 895 | — | — | — | — | — | 702 | 1.275 | 774 | 1.155 | 702 | 1.275 |
| Ib1 | 235 | — | — | — | 254 | 0.926 | — | — | — | — | — | — |
| Ib2 | 623 | 501 | 365 | 1.374 | — | — | — | — | — | — | — | — |
| Ib3 | 682 | 441 | 365 | 1.210 | — | — | — | — | — | — | — | — |
| IIa | 804 | — | — | — | — | — | 765 | 1.052 | 854 | 0.942 | 768 | 1.047 |
| IIa1 | 303 | — | — | — | 287 | 1.057 | — | — | — | — | — | — |
| IIa2 | 564 | 405 | 365 | 1.111 | — | — | — | — | — | — | — | — |
| IIa3 | 660 | 380 | 365 | 1.041 | — | — | — | — | — | — | — | — |
| IIb | 814 | — | — | — | — | — | 921 | 0.885 | 1001 | 0.814 | 921 | 0.885 |
| IIb1 | 348 | — | — | — | 476 | 0.731 | — | — | — | — | — | — |
| IIb2 | 532 | 411 | 365 | 1.127 | — | — | — | — | — | — | — | — |
| IIb3 | 674 | 390 | 365 | 1.070 | — | — | — | — | — | — | — | — |
| IIc | 917 | — | — | — | — | — | 888 | 1.033 | 952 | 0.963 | 888 | 1.033 |
| IIc1 | 523 | — | — | — | 572 | 0.914 | — | — | — | — | — | — |
| IIc2 | 471 | 490 | 365 | 1.343 | — | — | — | — | — | — | — | — |
| IIc3 | 657 | 420 | 365 | 1.151 | — | — | — | — | — | — | — | — |
| IIIb | 1138 | — | — | — | — | — | 1199 | 0.949 | 1276 | 0.892 | 1199 | 0.949 |
| IIIb1 | 719 | — | — | — | 754 | 0.954 | — | — | — | — | — | — |
| IIIb2 | 530 | 431 | 365 | 1.183 | — | — | — | — | — | — | — | — |
| IIIb3 | 579 | 455 | 365 | 1.247 | — | — | — | — | — | — | — | — |

**Table E1.29 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| II1b | 741 | — | — | — | — | — | 703 | 1.053 | 767 | 0.966 | 703 | 1.053 |
| II2b | 798 | — | — | — | — | — | 799 | 0.998 | 870 | 0.917 | 799 | 0.998 |
| II3b | 831 | — | — | — | — | — | 775 | 1.072 | 851 | 0.977 | 775 | 1.072 |
| II4b | 736 | — | — | — | — | — | 763 | 0.965 | 837 | 0.880 | 763 | 0.965 |
| II5b | 831 | — | — | — | — | — | 766 | 1.085 | 837 | 0.993 | 766 | 1.085 |
| II6b | 769 | — | — | — | — | — | 770 | 0.998 | 839 | 0.917 | 770 | 0.998 |
| II7b | 780 | — | — | — | — | — | 752 | 1.038 | 817 | 0.954 | 752 | 1.038 |
| II8b | 809 | — | — | — | — | — | 833 | 0.972 | 907 | 0.892 | 833 | 0.972 |

**Table E1.30** – Analysis of German Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ib | 781 | — | — | — | — | — | 604 | 1.294 | 677 | 1.154 | 614 | 1.273 |
| Ib1 | 291 | — | — | — | 239 | 1.218 | — | — | — | — | — | — |
| Ib2 | 549 | 559 | 368 | 1.520 | — | — | — | — | — | — | — | — |
| Ib3 | 594 | 446 | 368 | 1.212 | — | — | — | — | — | — | — | — |
| IIa | 840 | — | — | — | — | — | 735 | 1.142 | 823 | 1.020 | 744 | 1.129 |
| IIa1 | 332 | — | — | — | 260 | 1.274 | — | — | — | — | — | — |
| IIa2 | 623 | 487 | 368 | 1.324 | — | — | — | — | — | — | — | — |
| IIa3 | 689 | 419 | 368 | 1.137 | — | — | — | — | — | — | — | — |
| IIb | 954 | — | — | — | — | — | 805 | 1.185 | 883 | 1.080 | 805 | 1.185 |
| IIb1 | 409 | — | — | — | 368 | 1.113 | — | — | — | — | — | — |
| IIb2 | 505 | 488 | 368 | 1.325 | — | — | — | — | — | — | — | — |
| IIb3 | 673 | 404 | 368 | 1.098 | — | — | — | — | — | — | — | — |
| IIc | 1077 | — | — | — | — | — | 980 | 1.099 | 1040 | 1.036 | 980 | 1.099 |
| IIc1 | 573 | — | — | — | 605 | 0.947 | — | — | — | — | — | — |
| IIc2 | 433 | 500 | 368 | 1.357 | — | — | — | — | — | — | — | — |
| IIc3 | 685 | 403 | 368 | 1.094 | — | — | — | — | — | — | — | — |
| IIIb | 1148 | — | — | — | — | — | 1036 | 1.108 | 1104 | 1.040 | 1036 | 1.108 |
| IIIb1 | 806 | — | — | — | 663 | 1.217 | — | — | — | — | — | — |
| IIIb2 | 426 | 455 | 368 | 1.237 | — | — | — | — | — | — | — | — |
| IIIb3 | 603 | 394 | 368 | 1.071 | — | — | — | — | — | — | — | — |

**Table E1.30 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| II1b | 903 | — | — | — | — | — | 812 | 1.111 | 885 | 1.020 | 812 | 1.111 |
| II2b | 907 | — | — | — | — | — | 864 | 1.050 | 945 | 0.960 | 864 | 1.050 |
| II3b | 869 | — | — | — | — | — | 806 | 1.079 | 882 | 0.986 | 806 | 1.079 |
| II4b | 926 | — | — | — | — | — | 822 | 1.126 | 901 | 1.027 | 822 | 1.126 |
| II5b | 918 | — | — | — | — | — | 770 | 1.193 | 841 | 1.092 | 770 | 1.193 |
| II6b | 903 | — | — | — | — | — | 831 | 1.086 | 908 | 0.994 | 831 | 1.086 |
| II7b | 921 | — | — | — | — | — | 824 | 1.118 | 902 | 1.021 | 824 | 1.118 |
| II8b | 902 | — | — | — | — | — | 802 | 1.125 | 879 | 1.025 | 802 | 1.125 |

**Table E1.31** – Analysis of Italian Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ib | 834 | — | — | — | — | — | 674 | 1.237 | 747 | 1.117 | 674 | 1.237 |
| Ib1 | 277 | — | — | — | 315 | 0.881 | — | — | — | — | — | — |
| Ib2 | 562 | 485 | 371 | 1.309 | — | — | — | — | — | — | — | — |
| Ib3 | 687 | 470 | 371 | 1.269 | — | — | — | — | — | — | — | — |
| IIa | 844 | — | — | — | — | — | 839 | 1.006 | 940 | 0.897 | 853 | 0.989 |
| IIa1 | 358 | — | — | — | 385 | 0.930 | — | — | — | — | — | — |
| IIa2 | 663 | 454 | 371 | 1.225 | — | — | — | — | — | — | — | — |
| IIa3 | 698 | 449 | 371 | 1.212 | — | — | — | — | — | — | — | — |
| IIb | 827 | — | — | — | — | — | 785 | 1.054 | 863 | 0.958 | 785 | 1.054 |
| IIb1 | 339 | — | — | — | 391 | 0.868 | — | — | — | — | — | — |
| IIb2 | 535 | 447 | 371 | 1.205 | — | — | — | — | — | — | — | — |
| IIb3 | 740 | 435 | 371 | 1.172 | — | — | — | — | — | — | — | — |
| IIc | 1064 | — | — | — | — | — | 999 | 1.066 | 1069 | 0.996 | 999 | 1.066 |
| IIc1 | 571 | — | — | — | 637 | 0.896 | — | — | — | — | — | — |
| IIc2 | 495 | 500 | 371 | 1.350 | — | — | — | — | — | — | — | — |
| IIc3 | 756 | 426 | 371 | 1.150 | — | — | — | — | — | — | — | — |
| IIIb | 1152 | — | — | — | — | — | 1181 | 0.975 | 1260 | 0.914 | 1181 | 0.975 |
| IIIb1 | 559 | — | — | — | 710 | 0.788 | — | — | — | — | — | — |
| IIIb2 | 461 | 477 | 371 | 1.288 | — | — | — | — | — | — | — | — |
| IIIb3 | 640 | 414 | 371 | 1.116 | — | — | — | — | — | — | — | — |

**Table E1.31 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| II1b | 776 | — | — | — | — | — | 787 | 0.986 | 867 | 0.896 | 787 | 0.986 |
| II2b | 820 | — | — | — | — | — | 835 | 0.982 | 915 | 0.896 | 835 | 0.982 |
| II3b | 811 | — | — | — | — | — | 811 | 0.999 | 890 | 0.911 | 811 | 0.999 |
| II4b | 878 | — | — | — | — | — | 881 | 0.996 | 969 | 0.906 | 881 | 0.996 |
| II5b | 882 | — | — | — | — | — | 879 | 1.004 | 966 | 0.913 | 879 | 1.004 |
| II6b | 845 | — | — | — | — | — | 852 | 0.991 | 936 | 0.903 | 852 | 0.991 |
| II7b | 876 | — | — | — | — | — | 878 | 0.997 | 966 | 0.907 | 878 | 0.997 |
| II8b | 843 | — | — | — | — | — | 821 | 1.027 | 896 | 0.940 | 821 | 1.027 |

**Table E1.32** – Analysis of Swedish Test Results on St.52 Steel as Reported by Ligtenberg (1968)

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| Ib | 656 | — | — | — | — | — | 633 | 1.037 | 704 | 0.932 | 633 | 1.037 |
| Ib1 | 228 | — | — | — | 206 | 1.106 | — | — | — | — | — | — |
| Ib2 | 481 | 619 | 374 | 1.656 | — | — | — | — | — | — | — | — |
| Ib3 | 663 | 425 | 374 | 1.138 | — | — | — | — | — | — | — | — |
| IIa | 761 | — | — | — | — | — | 810 | 0.940 | 901 | 0.845 | 810 | 0.940 |
| IIa1 | 281 | — | — | — | 285 | 0.985 | — | — | — | — | — | — |
| IIa2 | 561 | 485 | 374 | 1.299 | — | — | — | — | — | — | — | — |
| IIa3 | 702 | 484 | 374 | 1.296 | — | — | — | — | — | — | — | — |
| IIb | 864 | — | — | — | — | — | 793 | 1.089 | 866 | 0.999 | 793 | 1.089 |
| IIb | 852 | — | — | — | — | — | 864 | 0.986 | 942 | 0.905 | 864 | 0.986 |
| IIb | 793 | — | — | — | — | — | 855 | 0.927 | 931 | 0.851 | 855 | 0.927 |
| IIb1 | 392 | — | — | — | 395 | 0.992 | — | — | — | — | — | — |
| IIb1 | 398 | — | — | — | 399 | 0.998 | — | — | — | — | — | — |
| IIb1 | 399 | — | — | — | 427 | 0.935 | — | — | — | — | — | — |
| IIb2 | 467 | 467 | 374 | 1.250 | — | — | — | — | — | — | — | — |
| IIb2 | 483 | 448 | 374 | 1.199 | — | — | — | — | — | — | — | — |
| IIb2 | 535 | 555 | 374 | 1.484 | — | — | — | — | — | — | — | — |
| IIb3 | 709 | 458 | 374 | 1.225 | — | — | — | — | — | — | — | — |
| IIb3 | 681 | 463 | 374 | 1.238 | — | — | — | — | — | — | — | — |
| IIb3 | 702 | 476 | 374 | 1.274 | — | — | — | — | — | — | — | — |

**Table E1.32 (cont.)**

| Specimen Designation | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| IIc | 1012 | — | — | — | — | — | 980 | 1.034 | 1041 | 0.972 | 980 | 1.034 |
| IIc1 | 618 | — | — | — | 628 | 0.984 | — | — | — | — | — | — |
| IIc2 | 466 | 629 | 374 | 1.683 | — | — | — | — | — | — | — | — |
| IIc3 | 705 | 471 | 374 | 1.262 | — | — | — | — | — | — | — | — |
| IIIb | 1048 | — | — | — | — | — | 984 | 1.065 | 1055 | 0.993 | 984 | 1.065 |
| IIIb1 | 710 | — | — | — | 634 | 1.120 | — | — | — | — | — | — |
| IIIb2 | 463 | 459 | 374 | 1.228 | — | — | — | — | — | — | — | — |
| IIIb3 | 657 | 396 | 374 | 1.061 | — | — | — | — | — | — | — | — |

**Table E1.33** – Summary of Analysis of Test Results as Reported by Ligtenberg (1968)

| Country | | Specimens with $a_2$ or $a_3$ only | | | Specimens with $a_1$ only | | | Specimens with $a_1$ and $a_2$ | | | | | | | Specimens with $a_1$, $a_2$ and $a_4$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | | | Equation 4.9 | |
| | Steel | Sample Size | $\rho_{M2}$ | $V_{M2}$ | Sample Size | $\rho_P$ | $V_P$ | Sample Size | $\rho_P$ | $V_P$ | $\rho_P$ | $V_P$ | $\rho_P$ | $V_P$ | Sample Size | $\rho_P$ | $V_P$ |
| England | St.37 | 18 | 1.077 | 0.096 | 9 | 1.044 | 0.115 | 16 | 1.085 | 0.095 | 0.992 | 0.101 | 1.082 | 0.100 | 9 | 0.899 | 0.363 |
| Japan | | 18 | 1.103 | 0.152 | 9 | 1.100 | 0.092 | 17 | 1.053 | 0.048 | 0.966 | 0.045 | 1.045 | 0.055 | — | — | — |
| USA | | 18 | 1.234 | 0.125 | 9 | 0.991 | 0.129 | 18 | 1.054 | 0.090 | 0.967 | 0.086 | 1.052 | 0.091 | 9 | 0.888 | 0.149 |
| France | | 18 | 1.087 | 0.124 | 9 | 1.047 | 0.074 | 18 | 1.091 | 0.106 | 1.001 | 0.103 | 1.088 | 0.104 | 9 | 0.854 | 0.119 |
| Germany | | 18 | 1.087 | 0.085 | 9 | 1.132 | 0.137 | 16 | 1.040 | 0.098 | 0.952 | 0.094 | 1.040 | 0.098 | — | — | — |
| Belgium | | 18 | 1.108 | 0.121 | 9 | 1.128 | 0.123 | 16 | 1.136 | 0.107 | 1.040 | 0.102 | 1.134 | 0.109 | 3 | 0.846 | 0.060 |
| Netherlands | | 17 | 1.210 | 0.077 | 9 | 1.043 | 0.093 | 17 | 0.962 | 0.071 | 0.882 | 0.074 | 0.960 | 0.070 | 3 | 0.888 | 0.039 |
| Canada | | 18 | 1.236 | 0.129 | 9 | 1.156 | 0.090 | 15 | 1.115 | 0.122 | 1.024 | 0.102 | 1.117 | 0.111 | — | — | — |
| Sweden | | 18 | 1.149 | 0.145 | 9 | 1.066 | 0.145 | 18 | 1.036 | 0.118 | 0.946 | 0.114 | 1.031 | 0.120 | — | — | — |
| Yugoslavia | | 18 | 1.195 | 0.091 | 18 | 0.954 | 0.142 | 18 | 1.003 | 0.103 | 0.922 | 0.120 | 1.003 | 0.117 | — | — | — |
| All specimens of St. 37 steel | | 179 | 1.147 | 0.126 | 99 | 1.053 | 0.130 | 169 | 1.051 | 0.111 | 0.965 | 0.107 | 1.050 | 0.110 | 33 | 0.878 | 0.211 |
| Netherlands | St.52 | 10 | 1.186 | 0.093 | 5 | 0.916 | 0.129 | 13 | 1.029 | 0.090 | 0.943 | 0.085 | 1.028 | 0.090 | — | — | — |
| Germany | | 10 | 1.238 | 0.117 | 5 | 1.154 | 0.112 | 13 | 1.132 | 0.055 | 1.035 | 0.048 | 1.129 | 0.051 | — | — | — |
| Italy | | 10 | 1.230 | 0.060 | 5 | 0.873 | 0.060 | 13 | 1.025 | 0.067 | 0.935 | 0.066 | 1.023 | 0.068 | — | — | — |
| Sweden | | 14 | 1.306 | 0.138 | 7 | 1.009 | 0.087 | 14 | 1.011 | 0.061 | 0.948 | 0.067 | 1.011 | 0.061 | — | — | — |
| All specimens of St.52 steel | | 44 | 1.246 | 0.113 | 22 | 0.992 | 0.139 | 53 | 1.054 | 0.083 | 0.965 | 0.077 | 1.047 | 0.080 | — | — | — |
| All specimens | | 223 | 1.167 | 0.128 | 121 | 1.042 | 0.133 | 222 | 1.052 | 0.105 | 0.965 | 0.100 | 1.050 | 0.104 | — | — | — |

**Table E2.1** – Weld Measurements and Test Results from Bornscheuer and Feder (1966)

| Series No. | Specimen | Weld Orientation | Nominal Values | | | Test Results | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Weld Length $L$ (mm) | Throat Size $a$ (mm) | $L/a$ | Throat Size $a$ (mm) | Ratio $\rho_G$ | $P_u$ (kN) | $A_{throat}$ (mm$^2$) | $\tau_u$ (MPa) |
| 1.11 | 1 | Longitudinal | 200 | 4 | 50 | 3.7 | 0.925 | 1478 | 2965 | 499 |
| | 2 | | | | | 3.6 | 0.900 | 1460 | 2827 | 516 |
| | 3 | | | | | 3.6 | 0.900 | 1469 | 2784 | 527 |
| 1.12 | 4 | | 300 | 4 | 75 | 3.6 | 0.900 | 2308 | 4325 | 534 |
| | 5 | | | | | 3.4 | 0.850 | 2261 | 4122 | 549 |
| | 6 | | | | | 3.9 | 0.975 | 2296 | 4678 | 491 |
| 1.21 | 7 | | 100 | 4 | 25 | 4.1 | 1.025 | 733 | 1636 | 448 |
| | 8 | | | | | 4.2 | 1.050 | 723 | 1656 | 437 |
| | 9 | | | | | 4.0 | 1.000 | 763 | 1586 | 481 |
| 1.22 | 10 | | 160 | 8 | 20 | 7.4 | 0.925 | 1988 | 4746 | 419 |
| | 11 | | | | | 7.7 | 0.963 | 2072 | 4893 | 423 |
| | 12 | | | | | 7.5 | 0.938 | 2080 | 4800 | 433 |
| 1.23 | 13 | | 240 | 12 | 20 | 11.3 | 0.942 | 3532 | 10947 | 323 |
| | 14 | | | | | 11.0 | 0.917 | 3610 | 10539 | 343 |
| | 15 | | | | | 11.0 | 0.917 | 3625 | 10573 | 343 |
| 1.31 | 16 | | 200 | 4 | 50 | 3.5 | 0.875 | 1403 | 2850 | 492 |
| | 17 | | | | | 3.3 | 0.825 | 1411 | 2668 | 529 |
| | 18 | | | | | 3.3 | 0.825 | 1413 | 2644 | 534 |
| 1.32 | 19 | | 300 | 4 | 75 | 4.2 | 1.050 | 2453 | 5036 | 487 |
| | 20 | | | | | 3.8 | 0.950 | 2438 | 4599 | 530 |
| | 21 | | | | | 3.9 | 0.975 | 2256 | 4713 | 479 |

**Table E2.1 (cont.)**

| Series No. | Specimen | Weld Orientation | Nominal Values | | | Test Results | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Weld Length $L$ (mm) | Throat Size $a$ (mm) | $L/a$ | Throat Size $a$ (mm) | Ratio $\rho_G$ | $P_u$ (kN) | $A_{throat}$ (mm$^2$) | $\tau_u$ (MPa) |
| 1.41 | 22 | Transverse | 100 | 4 | 25 | 4.3 | 1.075 | 694 | 844 | — |
| | 23 | | | | | 4.2 | 1.050 | 718 | 846 | — |
| | 24 | | | | | 4.3 | 1.075 | 765 | 887 | — |
| 1.42 | 25 | | 160 | 8 | 20 | 6.9 | 0.863 | 1572 | 2234 | — |
| | 26 | | | | | 8.0 | 1.000 | 1755 | 2574 | — |
| | 27 | | | | | 7.5 | 0.938 | 1863 | 2414 | — |
| 1.43 | 28 | | 240 | 12 | 20 | 10.9 | 0.908 | 3855 | 5241 | — |
| | 29 | | | | | 11.4 | 0.950 | 3787 | 5491 | — |
| 1.51 | 31 | Transverse + Longitudinal | 55 + 55 | 5 | 11 | —† | — | 771 | 1540 | — |
| | 32 | | | | | —† | — | 730 | 1633 | — |
| | 33 | | | | | —† | — | 749 | 1619 | — |
| | 34 | | | | | —† | — | 757 | 1626 | — |
| | 35 | | | | | —† | — | 769 | 1612 | — |

† Measured throat sizes were not reported

**Table E2.2** – Analysis of Test Results from Bornscheuer and Feder (1966)

| Series No. | Specimen | | Specimens with transverse weld only | | Specimens with transverse and longitudinal welds | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Model | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | | $P_u$ (kN) | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| 1.41 | 22 | 694 | 592 | 1.172 | — | — | — | — | — | — |
| | 23 | 718 | 593 | 1.211 | — | — | — | — | — | — |
| | 24 | 765 | 622 | 1.230 | — | — | — | — | — | — |
| 1.42 | 25 | 1572 | 1566 | 1.003 | — | — | — | — | — | — |
| | 26 | 1755 | 1805 | 0.972 | — | — | — | — | — | — |
| | 27 | 1863 | 1693 | 1.101 | — | — | — | — | — | — |
| 1.43 | 28 | 3855 | 3675 | 1.049 | — | — | — | — | — | — |
| | 29 | 3787 | 3850 | 0.984 | — | — | — | — | — | — |
| 1.51 | 31 | 771 | — | — | 768 | 1.004 | 840 | 0.918 | 768 | 1.004 |
| | 32 | 730 | — | — | 814 | 0.896 | 891 | 0.820 | 814 | 0.847 |
| | 33 | 749 | — | — | 807 | 0.927 | 883 | 0.848 | 807 | 0.841 |
| | 34 | 757 | — | — | 811 | 0.934 | 887 | 0.854 | 811 | 0.848 |
| | 35 | 769 | — | — | 804 | 0.957 | 879 | 0.875 | 804 | 0.868 |

**Table E3.1** – Weld Measurements and Test Results from Kato and Morita (1969)

| Specimen | Weld Orientation | Nominal Throat Size | | Nominal Throat Size | | | Test Results | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $a_1$ (mm) | $a_2$ (mm) | $a_1$ (mm) | $a_2$ (mm) | Ratio $\rho_G$ | $P_u$ (kN) | Throat Area $A_1$ ($mm^2$) | Throat Area $A_2$ ($mm^2$) |
| $S_2$5B | Longitudinal | — | 3.5 | — | 3.6 | 1.029 | 106 | — | 215 |
| $S_2$7B | | — | 4.9 | — | 5.1 | 1.041 | 185 | — | 421 |
| $S_2$10B | | — | 7.1 | — | 7.0 | 0.986 | 344 | — | 846 |
| $S_2$12B | | — | 8.5 | — | 8.1 | 0.953 | 473 | — | 1175 |
| $S_2$15B | | — | 10.6 | — | 10.7 | 1.009 | 824 | — | 1910 |
| $S_2$20B | | — | 14.1 | — | 14.2 | 1.007 | 1416 | — | 3446 |
| $S_2$22B | | — | 15.6 | — | 14.5 | 0.929 | 1552 | — | 3800 |
| $S_2$5R | Longitudinal | — | 3.5 | — | 3.4 | 0.971 | 78 | — | 204 |
| $S_2$10R | | — | 7.1 | — | 7.3 | 1.028 | 312 | — | 892 |
| $S_2$15R | | — | 10.6 | — | 10.7 | 1.009 | 1005 | — | 2966 |
| $S_2$20R | | — | 14.1 | — | 12.3 | 0.872 | 736 | — | 1934 |
| $S_1$5B | Transverse | 3.5 | — | 3.5 | — | 1.000 | 202 | 277 | — |
| $S_1$10B | | 7.1 | — | 7.2 | — | 1.014 | 340 | 571 | — |
| $S_1$15B | | 10.6 | — | 10.8 | — | 1.019 | 508 | 862 | — |
| $S_1$20B | | 14.1 | — | 14.1 | — | 1.000 | 662 | 1137 | — |
| $S_1$30B | | 21.2 | — | 21.2 | — | 1.000 | 870 | 1697 | — |
| $S_1$40B | | 28.3 | — | 28.3 | — | 1.000 | 1296 | 2259 | — |
| $S_1$5R | | 3.5 | — | 3.5 | — | 1.000 | 150 | 271 | — |
| $S_1$15R | | 10.6 | — | 10.7 | — | 1.009 | 452 | 848 | — |
| $S_1$40R | | 28.3 | — | 24.9 | — | 0.880 | 916 | 2005 | — |
| S5–5B | Longitudinal + Transverse | 3.5 | 3.5 | 3.7 | 3.7 | 1.057 / 1.057 | 578 | 488 | 494 |
| S15–5B | | 10.6 | 3.5 | 10.8 | 3.9 | 1.019 / 1.114 | 1366 | 1628 | 517 |
| S5–15B | | 3.5 | 10.6 | 4.0 | 10.8 | 1.143 / 1.019 | 931 | 538 | 1654 |

**Table E3.2** – Analysis of Test Results from Kato and Morita (1969)

| Specimen | | Specimens with $a_2$ only | | | Specimens with $a_1$ only | | Specimens with $a_1$ and $a_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | Equation 4.6a | | | Equation 4.7 | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| $S_2$5B | 106 | 491 | 379 | 1.297 | — | — | — | — | — | — | — | — |
| $S_2$7B | 185 | 439 | | 1.160 | — | — | — | — | — | — | — | — |
| $S_2$10B | 344 | 408 | | 1.077 | — | — | — | — | — | — | — | — |
| $S_2$12B | 473 | 403 | | 1.066 | — | — | — | — | — | — | — | — |
| $S_2$15B | 824 | 432 | | 1.141 | — | — | — | — | — | — | — | — |
| $S_2$20B | 1416 | 411 | | 1.086 | — | — | — | — | — | — | — | — |
| $S_2$22B | 1552 | 409 | | 1.080 | — | — | — | — | — | — | — | — |
| $S_2$5R | 78 | 385 | 333 | 1.155 | — | — | — | — | — | — | — | — |
| $S_2$10R | 312 | 350 | | 1.053 | — | — | — | — | — | — | — | — |
| $S_2$15R | 1005 | 339 | | 1.020 | — | — | — | — | — | — | — | — |
| $S_2$20R | 736 | 381 | | 1.146 | — | — | — | — | — | — | — | — |
| $S_1$5B | 202 | — | — | — | 178 | 1.136 | — | — | — | — | — | — |
| $S_1$10B | 340 | — | — | — | 366 | 0.930 | — | — | — | — | — | — |
| $S_1$15B | 508 | — | — | — | 553 | 0.920 | — | — | — | — | — | — |
| $S_1$20B | 662 | — | — | — | 729 | 0.908 | — | — | — | — | — | — |
| $S_1$30B | 870 | — | — | — | 1088 | 0.800 | — | — | — | — | — | — |
| $S_1$40B | 1296 | — | — | — | 1449 | 0.895 | — | — | — | — | — | — |
| $S_1$5R | 150 | — | — | — | 151 | 0.996 | — | — | — | — | — | — |
| $S_1$15R | 452 | — | — | — | 463 | 0.978 | — | — | — | — | — | — |
| $S_1$40R | 916 | — | — | — | 1095 | 0.838 | — | — | — | — | — | — |
| S5–5B | 578 | — | — | — | — | — | 493 | 1.175 | 524 | 1.104 | 493 | 1.175 |
| S15–5B | 1366 | — | — | — | — | — | 1232 | 1.110 | 1265 | 1.081 | 1232 | 1.110 |
| S5–15B | 931 | — | — | — | — | — | 946 | 0.985 | 1052 | 0.886 | 946 | 0.985 |

**Table E4.1** – Summary of Test Program from Butler and Kulak (1969)

| Weld Metal Classification | AWS E60XX (AWS, 1969) | | | | |
|---|---|---|---|---|---|
| Fabricator (welder) | fabrication was carried out by a local steel fabricator using qualified welders and standard shop procedure | | | | |
| Specified Tensile Strength | 414 MPa (60 ksi) | | | | |
| Welding Process | SMAW | | | | |
| Specimen Configuration | double lapped, 0° weld | double lapped, 30° weld | double lapped, 60° weld | double lapped, 90° weld | full size connection |
| Lap Plate Thickness (mm) | 12.7 | 15.9 | 12.7 | 12.7 | |
| Main Plate Thickness (mm) | 25.4 | 31.8 | 25.4 | 25.4 | |
| Base Metal Grade | CSA G40.12, 1964: specified yield stress of 303 MPa (44 ksi), and a minimum tensile strength of 427 MPa (62 ksi) | | | | |
| Test Temperature | room temperature | | | | |
| Plate Stress at Peak Load | elastic (calculated by the presented results) | | | | |
| Specimen Designation | L–1, L–2 , L–3, L–4, L– 5 | 30–1, 30–2, 30–3, 30–4, 30–5, 30–6 | 60–1, 60–2, 60–3, 60–4, 60–5, 60–6 | T–1, T–2, T–3, T–4, T–5, T–6 | B–1, B–2, B–3, B–4, B–5, B–6, B–7, B–8 |
| Nominal Leg Size (mm) | 6.4 | | | | |
| Number of Passes | 1 | | | | |

**Table E4.2** – Weld measurements and Test Results as Reported by Butler and Kulak (1969)

| Specimen | Average Weld Size (mm) | Ratio $\rho_G$ | Model | | | Equation 4.7 | |
|---|---|---|---|---|---|---|---|
| | | | Ultimate Load (kN/mm)† | | | Ratio $\rho_P$ | $V_P$ |
| | | | Mean | $\sigma$ | $V$ | | |
| L–1 | 7.4 | 1.160 | 1.91 | 0.117 | 0.061 | — | — |
| L–2 | 6.9 | 1.080 | | | | | |
| L–3 | 6.9 | 1.080 | | | | | |
| L–4 | 6.9 | 1.080 | | | | | |
| L–5 | 7.4 | 1.160 | | | | | |
| 30–1 | 6.9 | 1.080 | 2.56 | 0.005 | 0.002 | 1.225 | 0.002 |
| 30–2 | 6.1 | 0.960 | | | | | |
| 30–3 | 6.6 | 1.040 | | | | | |
| 30–4 | 6.4 | 1.000 | | | | | |
| 30–5 | 6.4 | 1.000 | | | | | |
| 30–6 | 7.1 | 1.120 | | | | | |
| 60–1 | 7.6 | 1.200 | 2.47 | 0.089 | 0.036 | 0.845 | 0.036 |
| 60–2 | 7.9 | 1.240 | | | | | |
| 60–3 | 7.4 | 1.160 | | | | | |
| 60–4 | 7.9 | 1.240 | | | | | |
| 60–5 | 7.6 | 1.200 | | | | | |
| 60–6 | 7.9 | 1.240 | | | | | |
| T–1 | 6.9 | 1.080 | 2.71 | 0.166 | 0.061 | 0.914 | 0.061 |
| T–2 | 7.4 | 1.160 | | | | | |
| T–3 | 7.9 | 1.240 | | | | | |
| T–4 | 7.4 | 1.160 | | | | | |
| T–5 | 6.6 | 1.040 | | | | | |
| T–6 | 7.9 | 1.240 | | | | | |
| B–1‡ | 7.2 | 1.132 | — | — | — | — | — |
| B–2 | 7.3 | 1.156 | — | — | — | — | — |
| B–3 | 7.5 | 1.188 | — | — | — | — | — |
| B–4 | 7.5 | 1.184 | — | — | — | — | — |
| B–5 | 7.6 | 1.196 | — | — | — | — | — |
| B–6 | 7.4 | 1.168 | — | — | — | — | — |
| B–7 | 7.7 | 1.208 | — | — | — | — | — |
| B–8 | 6.8 | 1.072 | — | — | — | — | — |
| All specimen | Mean $\rho_G$ | 1.138 | — | — | — | — | — |
| | $V_G$ | 0.069 | — | — | — | — | — |

† Load reported as capacity of per linear length (mm) weld.

‡ This group of specimens was loaded eccentrically.

**Table E5.1** – Weld Measurements from Dawe and Kulak (1972)

| Connection Type | Specimen | Weld Location | Average Weld Leg Size (mm) | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ |
|---|---|---|---|---|---|---|
| series A | A–1 | vertical weld only | 7.9 | 1.244 | | |
| | A–2 | vertical weld only | 7.9 | 1.244 | | |
| | A–3 | vertical weld only | 7.6 | 1.197 | | |
| | A–4 | vertical weld only | 7.6 | 1.197 | | |
| | A–5 | vertical weld only | 7.6 | 1.197 | | |
| | A–6 | vertical weld only | 8.1 | 1.276 | | |
| | A–7 | vertical weld only | 7.4 | 1.165 | | |
| | A–8 | vertical weld only | 7.9 | 1.244 | | |
| series B | B–1 | tension flange | 7.1 | 1.118 | | |
| | | web | 7.6 | 1.197 | | |
| | B–2 | tension flange | 7.9 | 1.244 | | |
| | | web | 7.6 | 1.197 | | |
| | B–3 | tension flange | 7.9 | 1.244 | | |
| | | web | 7.6 | 1.197 | | |
| | B–4 | tension flange | 7.9 | 1.244 | | |
| | | web | 7.6 | 1.197 | | |
| series C | C–1 | compression flange | 7.4 | 1.165 | | |
| | | tension flange | 7.6 | 1.197 | | |
| | | web | 7.9 | 1.244 | | |
| | C–2 | compression flange | 7.4 | 1.165 | | |
| | | tension flange | 7.4 | 1.165 | | |
| | | web | 7.4 | 1.165 | 1.158 | 0.075 |
| | C–3 | compression flange | 7.9 | 1.244 | | |
| | | tension flange | 8.1 | 1.276 | | |
| | | web | 6.9 | 1.087 | | |
| | C–4 | compression flange | 6.6 | 1.039 | | |
| | | tension flange | 7.4 | 1.165 | | |
| | | web | 8.1 | 1.276 | | |
| series 1 | 1–1 | longitudinal weld | 6.4 | 1.008 | | |
| | 1–2 | | 6.9 | 1.087 | | |
| | 1–3 | | 6.6 | 1.039 | | |
| | 1–4 | | 6.6 | 1.039 | | |
| | 1–5 | | 6.6 | 1.039 | | |
| series 2 | 2 - 1 | longitudinal weld | 6.9 | 1.087 | | |
| | 2–2 | | 6.4 | 1.008 | | |
| | 2–3 | | 6.4 | 1.008 | | |
| | 2–4 | | 6.4 | 1.008 | | |
| | 2–5 | | 6.6 | 1.039 | | |
| series 3 | 3–1 | longitudinal weld | 7.9 | 1.244 | | |
| | 3–2 | | 7.4 | 1.165 | | |
| | 3–3 | | 7.1 | 1.118 | | |
| | 3–4 | | 7.6 | 1.197 | | |
| | 3–5 | | 7.6 | 1.197 | | |

**Table E6.1** – Weld Measurements and Test Results from Clark (1971)

| Series | Specimen | Loading Angle | Nominal Throat Size (mm) | Average Throat Size (mm) | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ | Model | Equation 4.7 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $P_u / A_{throat}$ (MPa) | $\tau_u$ (MPa) | Ratio $\rho_P$ | Mean $\rho_P$ | $V_P$ |
| Series I | 1a | 0° | 5.6 | 5.2 | 0.929 | 0.985 | 0.065 | 325 | 343 | — | — | — |
| | 1b | | | 5.2 | 0.929 | | | 332 | | — | | — |
| | 2a | | | 5.1 | 0.905 | | | 329 | | — | | — |
| | 2b | | | 5.8 | 1.030 | | | 328 | | — | | — |
| | 3a | | | 6.1 | 1.082 | | | 337 | | — | | — |
| | 3b | | | 5.6 | 1.000 | | | 368 | | — | | — |
| | 4a | | | 6.0 | 1.071 | | | 340 | | — | | — |
| | 4b | | | 5.8 | 1.027 | | | 357 | | — | | — |
| | 5a | | | 6.1 | 1.082 | | | 352 | | — | | — |
| | 5b | | | 5.9 | 1.048 | | | 357 | | — | | — |
| Series II | 1a | 90° | 5.6 | 5.7 | 1.014 | | | 580 | — | 1.129 | 1.139 | 0.134 |
| | 1b | | | 5.6 | 1.007 | | | 561 | | 1.092 | | |
| | 2a | | | 5.3 | 0.952 | | | 590 | | 1.148 | | |
| | 2b | | | 5.3 | 0.952 | | | 609 | | 1.185 | | |
| Series III | 1a | 30° | 5.6 | 5.5 | 0.973 | | | 566 | | 1.404 | | |
| | 1b | | | 5.3 | 0.939 | | | 524 | | 1.300 | | |
| | 2a | 60° | 5.6 | 5.1 | 0.904 | | | 597 | | 1.242 | | |
| | 2b | | | 4.9 | 0.880 | | | 428 | | 0.891 | | |

**Table E7.1** – Weld Measurements as Reported by Swannell (1979b)

| Specimen | Nominal Leg Size (mm) | Measured Leg Size (mm) | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ |
|---|---|---|---|---|---|
| 1 | 6.4 | 6.6 | 1.031 | | |
| 2 | 6.4 | 6.4 | 1.000 | | |
| 3 | 6.4 | 6.6 | 1.031 | | |
| 4 | 6.4 | 6.8 | 1.063 | | |
| 5 | 6.4 | 6.7 | 1.047 | | |
| 6a | 6.4 | 6.9 | 1.078 | | |
| 6b | 6.4 | 6.7 | 1.047 | | |
| 6c | 6.4 | 6.8 | 1.063 | | |
| 6d | 6.4 | 7.2 | 1.125 | | |
| 6e | 6.4 | 7.0 | 1.094 | | |
| 6f | 6.4 | 6.8 | 1.063 | 1.070 | 0.031 |
| 7 | 6.4 | 6.8 | 1.063 | | |
| 8 | 6.4 | 6.8 | 1.063 | | |
| 9 | 6.4 | 6.9 | 1.078 | | |
| 10a | 6.4 | 6.4 | 1.000 | | |
| 10b | 6.4 | 7.1 | 1.109 | | |
| 10c | 6.4 | 6.8 | 1.063 | | |
| 10d | 6.4 | 6.8 | 1.063 | | |
| 10e | 6.4 | 7.1 | 1.109 | | |
| 10f | 6.4 | 6.7 | 1.047 | | |
| 11 | 6.4 | 6.9 | 1.078 | | |

**Table E7.2** – Analysis of Test Results as Reported by Swannell (1979b)

| Test Type | Series No. | Specimen | Model | Equation 4.6a | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $\sigma_u$ (MPa) | $\tau_u$ (MPa) | $0.67\sigma_u$ | Ratio $\rho_{M2}$ | Mean $\rho_{M2}$ | $V_{M2}$ |
| All Weld Metal Coupon | 1 | 1 | 546 | — | 361 | — | — | — |
| | | 2 | 531 | — | | — | — | — |
| Welded Joints with Longitudinal Welds only | 2 | 1 | — | 394 | — | 1.091 | 1.045 | 0.041 |
| | | 2 | — | 398 | — | 1.103 | | |
| | 3 | 1 | — | 373 | — | 1.033 | | |
| | | 2 | — | 374 | — | 1.036 | | |
| | 4 | 1 | — | 361 | — | 1.000 | | |
| | | 2 | — | 357 | — | 0.989 | | |
| | | 3 | — | 384 | — | 1.064 | | |

**Table E8.1** – Weld Measurements from Pham (1981)

| Specimen | Nominal Throat Size (mm) | Average Throat Size (mm) | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ |
|---|---|---|---|---|---|
| a–B–1 | 3.5 | 4.0 | 1.143 | 1.072 | 0.102 |
| a–B–2 | | 3.5 | 1.000 | | |
| a–B–3 | | 4.4 | 1.257 | | |
| a–B–4 | | 4.0 | 1.143 | | |
| a–B–5 | | 4.0 | 1.143 | | |
| a–B–6 | | 3.8 | 1.086 | | |
| b–A–1 | | 3.8 | 1.086 | | |
| b–A–2 | | 3.7 | 1.057 | | |
| b–A–3 | | 3.8 | 1.086 | | |
| b–A–4 | | 4.2 | 1.200 | | |
| b–B–1 | | 4.2 | 1.200 | | |
| b–B–2 | | 3.9 | 1.114 | | |
| b–B–3 | | 3.0 | 0.857 | | |
| b–B–4 | | 3.0 | 0.857 | | |
| c–A–1 | | 3.9 | 1.114 | | |
| c–A–2 | | 3.6 | 1.029 | | |
| c–B–1 | | 3.9 | 1.114 | | |
| c–A–3 | 7.1 | 7.3 | 1.028 | 1.058 | 0.051 |
| c–A–4 | | 7.4 | 1.042 | | |
| c–A–5 | | 7.3 | 1.028 | | |
| c–A–6 | | 7.1 | 1.000 | | |
| c–B–2 | | 8.0 | 1.127 | | |
| c–B–3 | | 7.9 | 1.143 | | |
| c–A–7 | 11.3 | 11.2 | 0.991 | 1.030 | 0.054 |
| c–A–8 | | 12.4 | 1.097 | | |
| c–B–4 | | 11.3 | 1.000 | | |

**Table E9.1** – Test Matrix of Test Program from Pham (1983a)

| weld metal classification | Fluxofil 11Ni (with $CO_2$ shield) | | | AWS class F70-EL12 | | |
|---|---|---|---|---|---|---|
| Tensile strength of electrode | 570 MPa | | | 646 MPa | | |
| Welding procedure | FCAW | | | SAW | | |
| Specimen configuration | Cruciform | | | Cruciform | | |
| Lap-plate thick (mm) | 20 | 32 | 50 | 20 | 32 | 50 |
| Main-plate thick (mm) | 20 | 32 | 50 | 20 | 32 | 50 |
| Specimen designation | 6F1, 6F2, 6F3, 6F4, 6F5, 6F6 | 10F1, 10F2, 10F3, 10F4, 10F5, 10F6 | 16F1, 16F2, 16F3, 16F4, 16F5, 16F6 | 6S1, 6S2, 6S3, 6S4, 6S5, 6S6 | 10S1, 10S2, 10S3, 10S4, 10S5, 10S6 | 16S1, 16S2, 16S3, 16S4, 16S5, 16S6 |
| Nominal leg size (mm) | 6 | 10 | 16 | 6 | 10 | 16 |



**Table E9.2** – Test Matrix of Test Program from Pham (1983b)

| Weld metal classification | Fluxofil 11Ni (with $CO_2$ shield) | | | AWS class F70-EL12 | | |
|---|---|---|---|---|---|---|
| Tensile strength of electrode | 570 MPa | | | 646 MPa | | |
| Welding procedure | FCAW | | | SAW | | |
| Specimen configuration | Werner Specimen | | | Werner Specimen | | |
| Lap-plate thick (mm) | 10 | 16 | 25 | 10 | 16 | 25 |
| Main-plate thick (mm) | 10 | 16 | 25 | 10 | 16 | 25 |
| Specimen designation | 6F7, 6F8, 6F9, 6F7#, 6F8#, 6F9# | 10F7, 10F8, 10F9, 10F10, 10F11, 10F12 | 16F7, 16F8, 16F9, 16F10, 16F11, 16F12 | 6S7, 6S7#, 6S9, 6S10#, 6S11, 6S11# | 10S7, 10S8, 10S9, 10S10, 10S11, 10S12 | 16S7, 16S8, 16S9, 16S10, 16S11, 16S12 |
| Nominal leg size (mm) | 6 | 10 | 16 | 6 | 10 | 16 |

**Table E9.3** – Weld Measurements from Pham (1983a)

| Specimen | Nominal Leg Size (mm) | Measured Dimensions | | | | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ |
|---|---|---|---|---|---|---|---|---|
| | | Leg Size $s_1$ (mm) | Leg Size $s_2$ (mm) | MTD (mm) | Length (mm) | | | |
| 6F1 | 6 | 9.5 | 8.0 | 6.1 | 30.9 | 1.443 | 1.326 | 0.045 |
| 6F2 | 6 | 9.0 | 7.0 | 5.5 | 30.1 | 1.303 | | |
| 6F3 | 6 | 8.0 | 8.0 | 5.7 | 31.0 | 1.334 | | |
| 6F4 | 6 | 9.0 | 7.0 | 5.5 | 30.6 | 1.303 | | |
| 6F5 | 6 | 9.0 | 7.0 | 5.5 | 30.0 | 1.303 | | |
| 6F6 | 6 | 8.5 | 7.0 | 5.4 | 30.7 | 1.274 | | |
| 10F1 | 10 | 10.0 | 9.5 | 6.9 | 49.2 | 0.974 | 1.010 | 0.065 |
| 10F2 | 10 | 10.5 | 10.5 | 7.4 | 49.3 | 1.050 | | |
| 10F3 | 10 | 9.5 | 9.5 | 6.7 | 50.0 | 0.950 | | |
| 10F4 | 10 | 9.5 | 9.5 | 6.7 | 49.3 | 0.950 | | |
| 10F5 | 10 | 12.0 | 10.5 | 7.9 | 51.1 | 1.118 | | |
| 10F6 | 10 | 9.5 | 11.0 | 7.2 | 51.4 | 1.017 | | |
| 16F1 | 16 | 18.5 | 16.5 | 12.3 | 81.0 | 1.089 | 1.130 | 0.106 |
| 16F2 | 16 | 21.0 | 18.9 | 14.0 | 80.1 | 1.242 | | |
| 16F3 | 16 | 16.0 | 15.5 | 11.1 | 80.8 | 0.984 | | |
| 16F4 | 16 | 17.0 | 15.5 | 11.5 | 80.6 | 1.013 | | |
| 16F5 | 16 | 20.6 | 20.1 | 14.4 | 79.2 | 1.272 | | |
| 16F6 | 16 | 18.0 | 20.0 | 13.4 | 79.4 | 1.183 | | |
| 6S1 | 6 | 8.0 | 7.0 | 5.3 | 29.5 | 1.242 | 1.322 | 0.031 |
| 6S2 | 6 | 10.0 | 7.0 | 5.7 | 29.3 | 1.352 | | |
| 6S3 | 6 | 9.5 | 7.0 | 5.6 | 29.5 | 1.328 | | |
| 6S4 | 6 | 10.0 | 7.0 | 5.7 | 30.7 | 1.352 | | |
| 6S5 | 6 | 9.5 | 7.0 | 5.6 | 31.7 | 1.328 | | |
| 6S6 | 6 | 9.5 | 7.0 | 5.6 | 29.8 | 1.328 | | |
| 10S1 | 10 | 13.5 | 12.5 | 9.2 | 48.8 | 1.297 | 1.224 | 0.031 |
| 10S2 | 10 | 12.5 | 11.5 | 8.5 | 50.3 | 1.197 | | |
| 10S3 | 10 | 12.5 | 12.0 | 8.7 | 50.4 | 1.224 | | |
| 10S4 | 10 | 12.5 | 12.0 | 8.7 | 50.6 | 1.224 | | |
| 10S5 | 10 | 12.0 | 12.0 | 8.5 | 50.1 | 1.200 | | |
| 10S6 | 10 | 12.0 | 12.0 | 8.5 | 49.4 | 1.200 | | |
| 16S1 | 16 | 18.0 | 16.5 | 12.2 | 79.9 | 1.075 | 1.068 | 0.049 |
| 16S2 | 16 | 17.0 | 17.0 | 12.0 | 78.8 | 1.063 | | |
| 16S3 | 16 | 17.0 | 16.0 | 11.7 | 80.9 | 1.030 | | |
| 16S4 | 16 | 17.0 | 16.0 | 11.7 | 80.5 | 1.030 | | |
| 16S5 | 16 | 17.5 | 16.0 | 11.8 | 81.3 | 1.044 | | |
| 16S6 | 16 | 19.5 | 18.0 | 13.2 | 81.5 | 1.169 | | |

**Table E9.4** – Weld Measurements from Pham (1983b)

| Specimen | Nominal Leg Size (mm) | Measured Dimensions | | | | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ |
|---|---|---|---|---|---|---|---|---|
| | | Leg Size $s_1$ (mm) | Leg Size $s_2$ (mm) | MTD (mm) | Length (mm) | | | |
| 6F7 | 6 | 7.3 | 8.0 | 5.4 | 40.7 | 1.275 | 1.294 | 0.013 |
| 6F8 | 6 | 7.0 | 8.6 | 5.4 | 39.9 | 1.300 | | |
| 6F9 | 6 | 7.3 | 8.4 | 5.5 | 40.8 | 1.308 | | |
| 6F7# | 6 | 7.3 | 8.0 | 5.4 | 40.4 | 1.275 | | |
| 6F8# | 6 | 7.0 | 8.6 | 5.4 | 40.9 | 1.300 | | |
| 6F9# | 6 | 7.3 | 8.4 | 5.5 | 40.5 | 1.308 | | |
| 10F7 | 10 | 9.5 | 10.8 | 7.1 | 75.0 | 1.015 | 1.003 | 0.040 |
| 10F8 | 10 | 9.6 | 10.4 | 7.1 | 75.1 | 1.000 | | |
| 10F9 | 10 | 9.4 | 10.8 | 7.1 | 75.0 | 1.010 | | |
| 10F10 | 10 | 8.5 | 10.3 | 6.6 | 75.1 | 0.940 | | |
| 10F11 | 10 | —† | —† | — | 75.0 | — | | |
| 10F12 | 10 | 10.6 | 10.4 | 7.4 | 75.0 | 1.050 | | |
| 16F7 | 16 | 14.1 | 18.1 | 11.1 | 132.2 | 1.006 | 0.987 | 0.031 |
| 16F8 | 16 | 15.1 | 16.5 | 11.1 | 132.3 | 0.988 | | |
| 16F9 | 16 | 13.9 | 16.5 | 10.6 | 132.2 | 0.950 | | |
| 16F10 | 16 | 15.1 | 15.4 | 10.8 | 132.1 | 0.953 | | |
| 16F11 | 16 | 15.3 | 16.6 | 11.3 | 131.9 | 0.997 | | |
| 16F12 | 16 | 15.1 | 17.8 | 11.5 | 131.9 | 1.028 | | |
| 6S7 | 6 | 8.6 | 8.9 | 6.2 | 40.0 | 1.458 | 1.492 | 0.032 |
| 6S7# | 6 | 8.6 | 8.9 | 6.2 | 40.0 | 1.458 | | |
| 6S9 | 6 | —† | —† | — | — | — | | |
| 6S10# | 6 | —† | —† | — | — | — | | |
| 6S11 | 6 | 9.4 | 8.9 | 6.5 | 40.1 | 1.525 | | |
| 6S11# | 6 | 9.4 | 8.9 | 6.5 | 40.1 | 1.525 | | |
| 10S7 | 10 | 12.5 | 11.8 | 8.6 | 75.1 | 1.215 | 1.216 | 0.038 |
| 10S8 | 10 | 11.5 | 12.3 | 8.4 | 75.1 | 1.190 | | |
| 10S9 | 10 | 11.5 | 12.3 | 8.4 | 75.1 | 1.190 | | |
| 10S10 | 10 | 11.3 | 12.3 | 8.3 | 75.3 | 1.180 | | |
| 10S11 | 10 | 11.7 | 12.6 | 8.6 | 75.0 | 1.215 | | |
| 10S12 | 10 | 13.1 | 13.0 | 9.2 | 75.0 | 1.305 | | |
| 16S7 | 16 | —† | 18.3 | — | 132.4 | — | 1.107 | 0.039 |
| 16S8 | 16 | 18.3 | 17.3 | 12.6 | 132.0 | 1.113 | | |
| 16S9 | 16 | 17.8 | 18.4 | 12.8 | 132.0 | 1.131 | | |
| 16S10 | 16 | 17.9 | 18.8 | 13.0 | 131.5 | 1.147 | | |
| 16S11 | 16 | 17.6 | 17.9 | 12.5 | 131.6 | 1.109 | | |
| 16S12 | 16 | 16.0 | 17.1 | 11.7 | 131.9 | 1.034 | | |

† Measured dimensions were not reported.

**Table E9.5** – Test Results and Analysis of the Test Program as Reported by Pham (1983a)

| Specimen | Model | | Equation 4.7 | | | |
|---|---|---|---|---|---|---|
| | $P_u$ (kN) | $A_{throat}$ (mm$^2$) | Predicted Load (kN) | Ratio $\rho_P$ | Mean $\rho_P$ | $V_P$ |
| 6F1 | 264 | 378 | 238 | 1.111 | 1.206 | 0.042 |
| 6F2 | 255 | 333 | 209 | 1.220 | | |
| 6F3 | 265 | 351 | 220 | 1.203 | | |
| 6F4 | 258 | 338 | 212 | 1.214 | | |
| 6F5 | 255 | 332 | 208 | 1.224 | | |
| 6F6 | 263 | 332 | 208 | 1.262 | | |
| 10F1 | 385 | 678 | 426 | 0.904 | 0.888 | 0.072 |
| 10F2 | 411 | 732 | 460 | 0.894 | | |
| 10F3 | 408 | 672 | 422 | 0.967 | | |
| 10F4 | 377 | 662 | 416 | 0.906 | | |
| 10F5 | 392 | 808 | 507 | 0.773 | | |
| 10F6 | 410 | 739 | 464 | 0.883 | | |
| 16F1 | 1184 | 1995 | 1253 | 0.945 | 0.906 | 0.099 |
| 16F2 | 1166 | 2251 | 1414 | 0.825 | | |
| 16F3 | 1126 | 1799 | 1130 | 0.996 | | |
| 16F4 | 1175 | 1846 | 1160 | 1.013 | | |
| 16F5 | 1179 | 2279 | 1432 | 0.824 | | |
| 16F6 | 1112 | 2125 | 1335 | 0.833 | | |
| 6S1 | 213 | 311 | 189 | 1.127 | 1.091 | 0.033 |
| 6S2 | 213 | 336 | 204 | 1.042 | | |
| 6S3 | 225 | 332 | 202 | 1.113 | | |
| 6S4 | 225 | 352 | 214 | 1.051 | | |
| 6S5 | 240 | 357 | 217 | 1.104 | | |
| 6S6 | 227 | 336 | 204 | 1.111 | | |
| 10S1 | 642 | 895 | 545 | 1.179 | 1.251 | 0.030 |
| 10S2 | 660 | 851 | 518 | 1.274 | | |
| 10S3 | 670 | 873 | 531 | 1.262 | | |
| 10S4 | 660 | 876 | 533 | 1.239 | | |
| 10S5 | 660 | 850 | 517 | 1.276 | | |
| 10S6 | 650 | 838 | 510 | 1.275 | | |
| 16S1 | 1157 | 1944 | 1182 | 0.979 | 0.981 | 0.054 |
| 16S2 | 1112 | 1894 | 1152 | 0.965 | | |
| 16S3 | 1188 | 1885 | 1147 | 1.036 | | |
| 16S4 | 1148 | 1876 | 1141 | 1.006 | | |
| 16S5 | 1183 | 1920 | 1168 | 1.013 | | |
| 16S6 | 1160 | 2156 | 1311 | 0.885 | | |

**Table E9.6** – Test Results and Analysis of the Test Program as Reported by Pham (1983b)

| Specimen | Model | | Equation 4.6a | | | | |
|---|---|---|---|---|---|---|---|
| | $P_u$ (kN) | $A_{throat}$ (mm$^2$) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Mean $\rho_{M2}$ | $V_{M2}$ |
| 6F7 | 81.50 | 155 | 525 | 382 | 1.374 | 1.226 | 0.156 |
| 6F8 | 84.00 | 156 | 537 | | 1.407 | | |
| 6F9 | 85.00 | 159 | 536 | | 1.403 | | |
| 6F7# | 65.80 | 155 | 424 | | 1.109 | | |
| 6F8# | 58.25 | 156 | 373 | | 0.976 | | |
| 6F9# | 65.75 | 159 | 414 | | 1.085 | | |
| 10F7 | 267.00 | 713 | 374 | 382 | 0.980 | 1.037 | 0.045 |
| 10F8 | 284.00 | 705 | 403 | | 1.054 | | |
| 10F9 | 282.00 | 709 | 398 | | 1.041 | | |
| 10F10 | 276.00 | 656 | 421 | | 1.102 | | |
| 10F11 | — | — | — | | — | | |
| 10F12 | 285.00 | 742 | 384 | | 1.005 | | |
| 16F7 | 689.00 | 1780 | 387 | 382 | 1.014 | 1.018 | 0.043 |
| 16F8 | 681.00 | 1782 | 382 | | 1.000 | | |
| 16F9 | 703.00 | 1701 | 413 | | 1.082 | | |
| 16F10 | 694.00 | 1725 | 402 | | 1.053 | | |
| 16F11 | 659.00 | 1800 | 366 | | 0.959 | | |
| 16F12 | 703.00 | 1842 | 382 | | 0.999 | | |
| 6S7 | 104.00 | 190 | 546 | 433 | 1.261 | 1.082 | 0.181 |
| 6S7# | 64.50 | 160 | 404 | | 0.934 | | |
| 6S9# | 77.80 | — | — | | — | | |
| 6S10# | — | — | — | | — | | |
| 6S11 | 93.00 | 173 | 537 | | 1.241 | | |
| 6S11# | 63.50 | 164 | 387 | | 0.894 | | |
| 10S7 | 320.00 | 858 | 373 | 433 | 0.862 | 0.894 | 0.067 |
| 10S8 | 310.00 | 840 | 369 | | 0.853 | | |
| 10S9 | 329.00 | 840 | 392 | | 0.905 | | |
| 10S10 | 326.00 | 832 | 392 | | 0.905 | | |
| 10S11 | 372.00 | 857 | 434 | | 1.002 | | |
| 10S12 | 334.00 | 923 | 362 | | 0.836 | | |
| 16S7 | 765.00 | — | — | 433 | — | 0.872 | 0.046 |
| 16S8 | 756.00 | 2011 | 376 | | 0.868 | | |
| 16S9 | 743.00 | 2047 | 363 | | 0.839 | | |
| 16S10 | 761.00 | 2074 | 367 | | 0.848 | | |
| 16S11 | 752.00 | 2008 | 375 | | 0.865 | | |
| 16S12 | 761.00 | 1869 | 407 | | 0.941 | | |

**Table E10.1** – Test Matrix of Test Program from Miazga and Kennedy (1986)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weld metal classification | CSA Standard W48.1-M80, E48014 | | | | | | |
| Electrode manufacturer | Hobart Brothers of Canada | | | | | | |
| Steel fabricator (welder) | Welding Research Laboratory of the Dept. of Mineral Eng. U of A | | | | | | |
| Specified tensile strength | 480MPa | | | | | | |
| Welding process | SMAW, Semi-automatic | | | | | | |
| Loading angle | 90° | 75° | 60° | 45° | 30° | 15° | 0° |
| Lap plate thickness (mm) | 9 mm | | | | | | |
| Main plate thickness (mm) | 18 mm | | | | | | |
| Base metal grade | CAN3-G40.21 - M81 grade 300W | | | | | | |
| Plate stress at peak load | elastic | | | | | | |
| Specimen designation | 90.1, 90.2, 90.3 | 75.1, 75.2, 75.3 | 60.1, 60.2, 60.3 | 45.1, 45.2, 45.3 | 30.1, 30.2, 30.3 | 15.1, 15.2, 15.3 | 00.1, 00.2, 00.3 |
| Nominal leg size (mm) | 5 mm | | | | | | |
| Number of passes | 1 pass | | | | | | |

**Table E10.1 (cont.)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weld metal classification | CSA Standard W48.1-M80, E48014 | | | | | | |
| Electrode manufacturer | Hobart Brothers of Canada | | | | | | |
| Steel fabricator (welder) | Welding Research Laboratory of the Dept. of Mineral Eng. U of A | | | | | | |
| Specified tensile strength | 480MPa | | | | | | |
| Welding process | SMAW, Semi-automatic | | | | | | |
| Loading angle | 90° | 75° | 60° | 45° | 30° | 15° | 0° |
| Lap plate thickness (mm) | 18 mm | | | | | | |
| Main plate thickness (mm) | 35 mm | | | | | | |
| Base metal grade | CAN3-G40.21 - M81 grade 300W | | | | | | |
| Plate stress at peak load | elastic | | | | | | |
| Specimen designation | 90.11, 90.12, 90.13 | 75.11, 75.12, 75.13 | 60.11, 60.12, 60.13 | 45.11, 45.12, 45.13 | 30.11, 30.12, 30.13 | 15.11, 15.12, 15.13 | 00.11, 00.12, 00.13 |
| Nominal leg size (mm) | 9 mm | | | | | | |
| Number of passes | 3 passes | | | | | | |

**Table E10.2** – Weld Measurements as Reported by Miazga and Kennedy (1986)

| Specimen | n † | Measured Leg Size | | | | Weld Length (mm) |
|---|---|---|---|---|---|---|
| | | Mean (mm) | s (mm) | $V$ | Ratio $\rho_G$ | |
| 90.1 | 44 | 5.25 | 0.31 | 0.058 | 1.050 | 200 |
| 90.2 | 44 | 5.33 | 0.34 | 0.064 | 1.066 | 200 |
| 90.3 | 44 | 5.29 | 0.39 | 0.072 | 1.058 | 201 |
| 75.1 | 44 | 5.14 | 0.36 | 0.070 | 1.028 | 215 |
| 75.2 | 44 | 5.01 | 0.35 | 0.071 | 1.002 | 211 |
| 75.3 | 44 | 5.12 | 0.29 | 0.060 | 1.024 | 210 |
| 60.1 | 48 | 5.12 | 0.33 | 0.064 | 1.024 | 230 |
| 60.2 | 48 | 5.06 | 0.32 | 0.063 | 1.012 | 231 |
| 60.3 | 48 | 5.03 | 0.37 | 0.072 | 1.006 | 226 |
| 45.1 | 48 | 5.37 | 0.52 | 0.099 | 1.074 | 204 |
| 45.2 | 48 | 5.10 | 0.52 | 0.101 | 1.020 | 200 |
| 45.3 | 48 | 5.12 | 0.37 | 0.071 | 1.024 | 196 |
| 30.1 | 64 | 5.31 | 0.40 | 0.075 | 1.062 | 294 |
| 30.2 | 62 | 5.50 | 0.39 | 0.071 | 1.100 | 302 |
| 30.3 | 60 | 5.27 | 0.34 | 0.065 | 1.054 | 296 |
| 15.1 | 58 | 5.19 | 0.50 | 0.099 | 1.038 | 306 |
| 15.2 | 58 | 5.14 | 0.37 | 0.072 | 1.028 | 313 |
| 15.3 | 59 | 5.09 | 0.45 | 0.089 | 1.018 | 311 |
| 00.1 | 72 | 4.94 | 0.40 | 0.081 | 0.988 | 316 |
| 00.2 | 72 | 5.22 | 0.39 | 0.075 | 1.044 | 309 |
| 00.3 | 72 | 5.16 | 0.32 | 0.062 | 1.032 | 315 |
| 90.11 | 44 | 9.10 | 0.49 | 0.054 | 1.011 | 197 |
| 90.12 | 44 | 9.26 | 0.39 | 0.043 | 1.029 | 200 |
| 90.13 | 44 | 9.16 | 0.54 | 0.058 | 1.018 | 200 |
| 75.11 | 44 | 9.18 | 0.58 | 0.064 | 1.020 | 211 |
| 75.12 | 44 | 9.08 | 0.53 | 0.058 | 1.009 | 207 |
| 75.13 | 44 | 9.24 | 0.42 | 0.045 | 1.027 | 209 |
| 60.11 | 48 | 9.42 | 0.38 | 0.041 | 1.047 | 226 |
| 60.12 | 48 | 9.65 | 0.35 | 0.036 | 1.072 | 229 |
| 60.13 | 48 | 9.88 | 0.41 | 0.042 | 1.098 | 228 |
| 45.11 | 56 | 9.43 | 0.50 | 0.054 | 1.048 | 272 |
| 45.12 | 56 | 9.46 | 0.48 | 0.050 | 1.051 | 279 |
| 45.13 | 58 | 9.18 | 0.50 | 0.056 | 1.020 | 279 |
| 30.11 | 64 | 9.41 | 0.36 | 0.038 | 1.046 | 296 |
| 30.12 | 60 | 9.16 | 0.40 | 0.043 | 1.018 | 296 |
| 30.13 | 58 | 9.74 | 0.40 | 0.041 | 1.082 | 294 |
| 15.11 | 54 | 8.79 | 0.34 | 0.088 | 0.977 | 300 |
| 15.12 | 52 | 9.23 | 0.40 | 0.044 | 1.026 | 294 |
| 15.13 | 54 | 9.06 | 0.38 | 0.042 | 1.007 | 294 |
| 00.11 | 64 | 9.50 | 0.35 | 0.037 | 1.056 | 300 |
| 00.12 | 72 | 9.10 | 0.44 | 0.049 | 1.011 | 321 |
| 00.13 | 72 | 9.20 | 0.34 | 0.037 | 1.022 | 316 |

† Number of measurements.

**Table E10.3** – Summary of Weld Measurements of Test Program as Reported by Miazga and Kennedy (1986)

| | Weld Size | |
|---|---|---|
| | 5 mm | 9 mm |
| Mean Measured Leg Size (mm) | 5.18 | 9.30 |
| s (mm) | 0.13 | 0.25 |
| $V$ | 0.026 | 0.027 |
| Mean of Mean/Nominal $\rho_G$ | 1.036 | 1.033 |
| $V_G$ | 0.026 | 0.027 |

**Table E10.4** – Test Results and Analysis as Reported by Miazga and Kennedy (1986)

| Specimen | Model | | Equation 4.6a | | | Equation 4.7 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $P_u$ (kN) | $A_{throat}$ (mm$^2$) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Mean $\rho_P$ | $V_P$ |
| 90.1 | 421 | 742 | — | — | — | 458 | 0.920 | 0.954 | 0.056 |
| 90.2 | 431 | 754 | — | — | — | 465 | 0.928 | | |
| 90.3 | 407 | 752 | — | — | — | 464 | 0.879 | | |
| 90.11 | 789 | 1267 | — | — | — | 782 | 1.010 | | |
| 90.12 | 807 | 1309 | — | — | — | 808 | 1.000 | | |
| 90.13 | 791 | 1295 | — | — | — | 799 | 0.990 | | |
| 75.1 | 466 | 781 | — | — | — | 473 | 0.984 | 0.996 | 0.018 |
| 75.2 | 451 | 747 | — | — | — | 453 | 0.996 | | |
| 75.3 | 471 | 760 | — | — | — | 461 | 1.022 | | |
| 75.11 | 822 | 1369 | — | — | — | 830 | 0.990 | | |
| 75.12 | 810 | 1329 | — | — | — | 805 | 1.006 | | |
| 75.13 | 805 | 1365 | — | — | — | 827 | 0.972 | | |
| 60.1 | 568 | 833 | — | — | — | 481 | 1.183 | 1.105 | 0.112 |
| 60.2 | 566 | 826 | — | — | — | 477 | 1.188 | | |
| 60.3 | 589 | 804 | — | — | — | 464 | 1.270 | | |
| 60.11 | 895 | 1505 | — | — | — | 868 | 1.031 | | |
| 60.12 | 892 | 1562 | — | — | — | 901 | 0.989 | | |
| 60.13 | 894 | 1593 | — | — | — | 919 | 0.973 | | |
| 45.1 | 447 | 775 | — | — | — | 413 | 1.081 | 0.990 | 0.129 |
| 45.2 | 433 | 721 | — | — | — | 384 | 1.126 | | |
| 45.3 | 419 | 709 | — | — | — | 378 | 1.107 | | |
| 45.11 | 842 | 1813 | — | — | — | 966 | 0.871 | | |
| 45.12 | 858 | 1866 | — | — | — | 995 | 0.862 | | |
| 45.13 | 861 | 1811 | — | — | — | 965 | 0.891 | | |
| 30.1 | 614 | 1104 | — | — | — | 534 | 1.150 | 1.079 | 0.056 |
| 30.2 | 626 | 1174 | — | — | — | 568 | 1.103 | | |
| 30.3 | 610 | 1103 | — | — | — | 534 | 1.143 | | |
| 30.11 | 980 | 1969 | — | — | — | 953 | 1.029 | | |
| 30.12 | 968 | 1917 | — | — | — | 928 | 1.044 | | |
| 30.13 | 989 | 2025 | — | — | — | 980 | 1.009 | | |
| 15.1 | 484 | 1123 | — | — | — | 492 | 0.984 | 0.953 | 0.051 |
| 15.2 | 477 | 1137 | — | — | — | 498 | 0.957 | | |
| 15.3 | 482 | 1119 | — | — | — | 490 | 0.983 | | |
| 15.11 | 773 | 1864 | — | — | — | 816 | 0.946 | | |
| 15.12 | 724 | 1919 | — | — | — | 841 | 0.861 | | |
| 15.13 | 815 | 1883 | — | — | — | 825 | 0.987 | | |
| 00.1 | 513 | 1104 | 464 | 360 | 1.284 | — | — | — | — |
| 00.2 | 487 | 1140 | 427 | | 1.186 | — | — | — | — |
| 00.3 | 483 | 1149 | 420 | | 1.167 | — | — | — | — |
| 00.11 | 752 | 2015 | 373 | | 1.036 | — | — | — | — |
| 00.12 | 825 | 2065 | 399 | | 1.108 | — | — | — | — |
| 00.13 | 787 | 2055 | 383 | | 1.064 | — | — | — | — |

**Table E11.1** – Test Matrix of Test Program from Bowman and Quinn (1994)

| Weld metal classification | E7018, 3/16-in diameter electrode | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Specified tensile strength | 496 MPa (72 ksi ) | | | | | | | | | |
| Welding process | SMAW | | | | | | | | | |
| Weld orientation | Longitudinal | | | Transverse | | | Longitudinal | | Transverse | |
| Lap plate thick (mm) | 25.4 | 38.1 | 50.8 | 12.7 | 19.1 | 25.4 | 25.4 | 50.8 | 12.7 | 25.4 |
| Main plate thick (mm) | 25.4 | 38.1 | 50.8 | 25.4 | 38.1 | 50.8 | 25.4 | 50.8 | 25.4 | 50.8 |
| Base metal grade | ASTM A572 Grade 50 | | | | | | | | | |
| Plate stress at peak load | elastic | | | | | | | | | |
| Specimen designation | 1–2–L–0<br>2–2–L–0 | 3–3–L–0<br>4–3–L–0 | 5–4–L–0<br>6–4–L–0 | 7–2–T–0<br>8–2–T–0 | 9–3–T–0<br>10–3–T–0 | 11–4–T–0<br>12–4–T–0 | 13–2–L–1<br>14–2–L–2 | 15–4–L–1 | 16–2–T–1<br>17–2–T–2 | 18–4–T–1 |
| Nominal leg size (mm) | 6.4 | 9.5 | 12.7 | 6.4 | 9.5 | 12.7 | 6.4 | 12.7 | 6.4 | 12.7 |
| Root opening (mm) | none | | | none | | | 1.6 | 1.6 | 1.6 | 1.6 |
| Number of passes | 1 | 2 | 3 or 4 | 1 | 2 | 4 | 1 | 4 | 1 | 4 |

**Table E11.2** – Weld Measurements as Reported by Bowman and Quinn (1994)

| Specimen | Nominal Leg Size (mm) | Bottom Leg Size (mm) | Top Leg Size (mm) | MTD (mm) | Ratio $\rho_G$ | Mean $\rho_G$ | $V_G$ |
|---|---|---|---|---|---|---|---|
| 1–2–L–0 | 6.4 | 7.0 | 6.8 | 4.9 | 1.086 | 1.182 | 0.082 |
| 2–2–L–0 | | 7.2 | 7.0 | 5.0 | 1.122 | | |
| 7–2–T–0 | | 8.1 | 7.8 | 5.6 | 1.246 | | |
| 8–2–T–0 | | 7.8 | 9.3 | 6.0 | 1.337 | | |
| 13–2–L–1 | | 6.7 | 8.2 | 5.2 | 1.158 | | |
| 14–2–L–2 | | 5.9 | 8.3 | 4.8 | 1.066 | | |
| 16–2–T–1 | | 7.8 | 8.6 | 5.8 | 1.286 | | |
| 17–2–T–2 | | 6.4 | 9.0 | 5.2 | 1.158 | | |
| 3–3–L–0 | 9.5 | 10.4 | 11.0 | 7.6 | 1.121 | 1.128 | 0.040 |
| 4–3–L–0 | | 9.7 | 10.7 | 7.2 | 1.067 | | |
| 9–3–T–0 | | 10.5 | 11.9 | 7.9 | 1.169 | | |
| 10–3–T–0 | | 10.7 | 11.3 | 7.8 | 1.154 | | |
| 5–4–L–0 | 12.7 | 13.7 | 13.5 | 9.6 | 1.070 | 1.087 | 0.030 |
| 6–4–L–0 | | 14.5 | 14.1 | 10.1 | 1.126 | | |
| 11–4–T–0 | | 14.0 | 12.6 | 9.4 | 1.047 | | |
| 12–4–T–0 | | 13.7 | 13.2 | 9.5 | 1.058 | | |
| 15–4–L–1 | | 14.5 | 13.6 | 9.9 | 1.105 | | |
| 18–4–T–1 | | 15.7 | 13.0 | 10.0 | 1.115 | | |

**Table E11.3** – Analysis of Test Program as Reported by Bowman and Quinn (1994)

| Specimen | Model | | Equation 4.6a | | | Equation 4.7 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $P_u$ (kN) | $A_{throat}$ (mm$^2$) | $\tau_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio $\rho_{M2}$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Mean $\rho_P$ | $V_P$ |
| 1–2–L–0 | 1099 | 1952 | 563 | 319 | 1.766 | — | — | — | — |
| 2–2–L–0 | 1081 | 2024 | 534 | | 1.676 | — | — | — | — |
| 3–3–L–0 | 1495 | 3027 | 494 | | 1.549 | — | — | — | — |
| 4–3–L–0 | 1477 | 2868 | 515 | | 1.615 | — | — | — | — |
| 5–4–L–0 | 1566 | 3856 | 406 | | 1.274 | — | — | — | — |
| 6–4–L–0 | 1690 | 4154 | 407 | | 1.276 | — | — | — | — |
| 7–2–T–0 | 818 | 1126 | — | — | — | 821 | 0.996 | 0.956 | 0.030 |
| 8–2–T–0 | 845 | 1208 | — | — | — | 881 | 0.959 | | |
| 9–3–T–0 | 1099 | 1609 | — | — | — | 1173 | 0.936 | | |
| 10–3–T–0 | 1139 | 1587 | — | — | — | 1157 | 0.984 | | |
| 11–4–T–0 | 1303 | 1912 | — | — | — | 1394 | 0.934 | | |
| 12–4–T–0 | 1308 | 1933 | — | — | — | 1410 | 0.927 | | |

**Table E12.1** – Weld Size Measurements from Ng *et al.* (2002) – 6.4 mm welds

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| T1–1 | 6.4 | Front | 6.5 | 6.6 | 5.7 | 4.6 | 1.231 | 1.231 | 1.024 |
| | | Back | 5.7 | 6.3 | 5.2 | 4.2 | 1.230 | 1.226 | 0.934 |
| T1–2 | 6.4 | Front | 6.5 | 6.2 | 5.5 | 4.5 | 1.226 | 1.225 | 0.992 |
| | | Back | 6.2 | 5.9 | 5.3 | 4.3 | 1.240 | 1.239 | 0.945 |
| T1–3 | 6.4 | Front | 6.0 | 6.5 | 5 | 4.4 | 1.134 | 1.132 | 0.974 |
| | | Back | 6.0 | 6.6 | 5.1 | 4.4 | 1.149 | 1.145 | 0.981 |
| T2–1 | 6.4 | Front | 5.5 | 6.2 | 4.1 | 4.1 | 0.996 | 0.991 | 0.909 |
| | | Back | 6.6 | 6.1 | 4.4 | 4.5 | 0.982 | 0.980 | 0.990 |
| T2–2 | 6.4 | Front | 6.0 | 6.1 | 4.4 | 4.3 | 1.029 | 1.029 | 0.945 |
| | | Back | 6.1 | 6.2 | 4.3 | 4.3 | 0.989 | 0.989 | 0.961 |
| T2–3 | 6.4 | Front | 6.1 | 6.7 | 4.7 | 4.5 | 1.042 | 1.039 | 0.997 |
| | | Back | 6.4 | 5.8 | 4.6 | 4.3 | 1.070 | 1.067 | 0.950 |
| T3–1 | 6.4 | Front | 7.5 | 6.6 | 5.4 | 5.0 | 1.090 | 1.083 | 1.095 |
| | | Back | 7.9 | 7.4 | 5.2 | 5.4 | 0.963 | 0.961 | 1.194 |
| T3–2 | 6.4 | Front | 8.0 | 6.8 | 5.4 | 5.2 | 1.042 | 1.032 | 1.145 |
| | | Back | 8.2 | 7.2 | 5.3 | 5.4 | 0.980 | 0.974 | 1.196 |
| T3–3 | 6.4 | Front | 7.6 | 7.3 | 5.4 | 5.3 | 1.026 | 1.025 | 1.164 |
| | | Back | 7.9 | 6.9 | 5.3 | 5.2 | 1.020 | 1.013 | 1.149 |
| T4–1 | 6.4 | Front | 5.9 | 6.2 | 5.4 | 4.3 | 1.263 | 1.262 | 0.945 |
| | | Back | 6.1 | 6.1 | 5.5 | 4.3 | 1.275 | 1.275 | 0.953 |
| T4–2 | 6.4 | Front | 6.1 | 6.4 | 5.4 | 4.4 | 1.223 | 1.222 | 0.976 |
| | | Back | 6.3 | 6.1 | 5.6 | 4.4 | 1.278 | 1.278 | 0.969 |
| T4–3 | 6.4 | Front | 6.0 | 6.3 | 5.2 | 4.3 | 1.197 | 1.196 | 0.960 |
| | | Back | 6.0 | 6.0 | 5.5 | 4.2 | 1.296 | 1.297 | 0.938 |
| T5–1 | 6.4 | Front | 6.4 | 5.8 | 4.8 | 4.3 | 1.117 | 1.113 | 0.950 |
| | | Back | 6.0 | 6.1 | 5 | 4.3 | 1.169 | 1.169 | 0.945 |
| T5–2 | 6.4 | Front | 6.5 | 5.8 | 4.9 | 4.3 | 1.132 | 1.127 | 0.956 |
| | | Back | 6.3 | 6.2 | 5 | 4.4 | 1.131 | 1.132 | 0.977 |
| T5–3 | 6.4 | Front | 6.3 | 5.8 | 4.9 | 4.3 | 1.148 | 1.146 | 0.943 |
| | | Back | 5.8 | 5.9 | 4.7 | 4.1 | 1.136 | 1.136 | 0.914 |
| T6–1 | 6.4 | Front | 6.6 | 5.1 | 4.6 | 4.0 | 1.140 | 1.112 | 0.892 |
| | | Back | 6.5 | 5.5 | 4.7 | 4.2 | 1.119 | 1.108 | 0.928 |
| T6–2 | 6.4 | Front | 6.3 | 5.7 | 4.7 | 4.2 | 1.112 | 1.108 | 0.934 |
| | | Back | 6.7 | 5.1 | 4.4 | 4.1 | 1.084 | 1.055 | 0.897 |
| T6–3 | 6.4 | Front | 6.5 | 5.8 | 4.8 | 4.3 | 1.109 | 1.104 | 0.956 |
| | | Back | 6.5 | 5.4 | 4.5 | 4.2 | 1.083 | 1.070 | 0.918 |
| T7–1 | 6.4 | Front | 6.5 | 5.8 | 4.4 | 4.3 | 1.017 | 1.012 | 0.956 |
| | | Back | 6.5 | 5.4 | 4.7 | 4.2 | 1.132 | 1.117 | 0.918 |
| T7–2 | 6.4 | Front | 5.1 | 4.5 | 3.9 | 3.4 | 1.156 | 1.149 | 0.746 |
| | | Back | 5.9 | 4.4 | 4 | 3.5 | 1.134 | 1.099 | 0.780 |
| T7–3 | 6.4 | Front | 5.2 | 4.5 | 4.2 | 3.4 | 1.234 | 1.225 | 0.752 |
| | | Back | 5.6 | 4.7 | 4.4 | 3.6 | 1.222 | 1.208 | 0.796 |
| T8–1 | 6.4 | Front | 5.9 | 7.3 | 5.8 | 4.6 | 1.264 | 1.243 | 1.014 |
| | | Back | 6.5 | 7.6 | 6.2 | 4.9 | 1.255 | 1.244 | 1.092 |

**Table E12.1 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| T8–2 | 6.4 | Front | 6.0 | 7.7 | 6.1 | 4.7 | 1.289 | 1.260 | 1.046 |
| | | Back | 6.5 | 7.3 | 6.1 | 4.9 | 1.257 | 1.250 | 1.073 |
| T8–3 | 6.4 | Front | 6.5 | 7.8 | 6.2 | 5.0 | 1.242 | 1.226 | 1.104 |
| | | Back | 6.9 | 7.1 | 6.1 | 4.9 | 1.233 | 1.233 | 1.094 |
| T9–1 | 6.4 | Front | 7.4 | 6.0 | 5.6 | 4.7 | 1.202 | 1.182 | 1.030 |
| | | Back | 8.6 | 5.8 | 5.5 | 4.8 | 1.144 | 1.080 | 1.063 |
| T9–2 | 6.4 | Front | 8.2 | 5.6 | 5.3 | 4.6 | 1.146 | 1.086 | 1.022 |
| | | Back | 8.3 | 6.1 | 5.3 | 4.9 | 1.078 | 1.041 | 1.086 |
| T9–3 | 6.4 | Front | 8.3 | 6.1 | 6 | 4.9 | 1.221 | 1.179 | 1.086 |
| | | Back | 8.0 | 6.1 | 5.6 | 4.9 | 1.154 | 1.124 | 1.072 |
| T10–1 | 6.4 | Front | 7.7 | 6.6 | 5.9 | 5.0 | 1.177 | 1.167 | 1.107 |
| | | Back | 8.8 | 6.6 | 6.5 | 5.3 | 1.231 | 1.194 | 1.167 |
| T10–2 | 6.4 | Front | 7.9 | 6.3 | 5.8 | 4.9 | 1.178 | 1.155 | 1.089 |
| | | Back | 8.2 | 6.3 | 6.1 | 5.0 | 1.221 | 1.190 | 1.104 |
| T10–3 | 6.4 | Front | 7.8 | 6.3 | 6.1 | 4.9 | 1.245 | 1.224 | 1.083 |
| | | Back | 8.6 | 6.6 | 6.1 | 5.2 | 1.165 | 1.135 | 1.157 |
| T11–1 | 6.4 | Front | 6.4 | 6.7 | 6.2 | 4.6 | 1.340 | 1.339 | 1.023 |
| | | Back | 7.6 | 6.8 | 6.3 | 5.1 | 1.243 | 1.238 | 1.120 |
| T11–2 | 6.4 | Front | 6.7 | 7.2 | 6.3 | 4.9 | 1.284 | 1.282 | 1.084 |
| | | Back | 7.1 | 6.8 | 5.9 | 4.9 | 1.201 | 1.201 | 1.085 |
| T11–3 | 6.4 | Front | 6.5 | 7.2 | 6.2 | 4.8 | 1.285 | 1.280 | 1.066 |
| | | Back | 7.1 | 6.9 | 6.3 | 4.9 | 1.273 | 1.273 | 1.094 |
| T12–1 | 6.4 | Front | 7.9 | 6.3 | 6.1 | 4.9 | 1.238 | 1.215 | 1.089 |
| | | Back | 7.8 | 5.4 | 5.1 | 4.4 | 1.149 | 1.093 | 0.981 |
| T12–2 | 6.4 | Front | 8.0 | 5.9 | 5.7 | 4.7 | 1.200 | 1.160 | 1.049 |
| | | Back | 7.8 | 5.1 | 5.1 | 4.3 | 1.195 | 1.118 | 0.943 |
| T12–3 | 6.4 | Front | 7.5 | 6.2 | 5.7 | 4.8 | 1.193 | 1.177 | 1.056 |
| | | Back | 8.2 | 5.4 | 5.1 | 4.5 | 1.131 | 1.061 | 0.997 |
| T13–1 | 6.4 | Front | 6.7 | 5.2 | 4.8 | 4.1 | 1.168 | 1.141 | 0.908 |
| | | Back | 6.8 | 6.6 | 4.8 | 4.7 | 1.014 | 1.013 | 1.047 |
| T13–2 | 6.4 | Front | 6.5 | 6.0 | 5.1 | 4.4 | 1.157 | 1.154 | 0.974 |
| | | Back | 7.3 | 5.9 | 5.5 | 4.6 | 1.199 | 1.179 | 1.014 |
| T13–3 | 6.4 | Front | 6.2 | 5.6 | 4.9 | 4.2 | 1.179 | 1.175 | 0.918 |
| | | Back | 5.5 | 5.8 | 5 | 4.0 | 1.253 | 1.252 | 0.882 |
| T14–1 | 6.4 | Front | 8.2 | 6.8 | 6.2 | 5.2 | 1.184 | 1.169 | 1.157 |
| | | Back | 8.7 | 6.9 | 6 | 5.4 | 1.110 | 1.088 | 1.195 |
| T14–2 | 6.4 | Front | 8.3 | 6.8 | 5.9 | 5.3 | 1.122 | 1.105 | 1.163 |
| | | Back | 8.7 | 6.7 | 5.8 | 5.3 | 1.093 | 1.065 | 1.173 |
| T14–3 | 6.4 | Front | 7.9 | 6.9 | 6.1 | 5.2 | 1.174 | 1.166 | 1.149 |
| | | Back | 8.5 | 6.6 | 5.9 | 5.2 | 1.132 | 1.105 | 1.152 |
| T15–1 | 6.4 | Front | 6.8 | 6.7 | 5.5 | 4.8 | 1.152 | 1.152 | 1.055 |
| | | Back | 7.7 | 6.8 | 6.3 | 5.1 | 1.236 | 1.229 | 1.126 |

**Table E12.1 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| T15–2 | 6.4 | Front | 7.4 | 7.3 | 5.9 | 5.2 | 1.135 | 1.135 | 1.149 |
| | | Back | 7.7 | 7.3 | 6.2 | 5.3 | 1.170 | 1.169 | 1.171 |
| T15–3 | 6.4 | Front | 7.2 | 7.0 | 5.8 | 5.0 | 1.156 | 1.155 | 1.109 |
| | | Back | 7.5 | 7.1 | 6.2 | 5.2 | 1.202 | 1.201 | 1.140 |
| T16–1 | 6.4 | Front | 6.7 | 7.1 | 5.4 | 4.9 | 1.108 | 1.107 | 1.077 |
| | | Back | 7.7 | 7.5 | 6.5 | 5.4 | 1.210 | 1.210 | 1.187 |
| T16–2 | 6.4 | Front | 6.7 | 6.8 | 5.4 | 4.8 | 1.131 | 1.132 | 1.055 |
| | | Back | 8.1 | 7.9 | 6.5 | 5.7 | 1.149 | 1.149 | 1.250 |
| T16–3 | 6.4 | Front | 6.9 | 7.1 | 5.4 | 4.9 | 1.091 | 1.091 | 1.094 |
| | | Back | 7.2 | 6.5 | 5.8 | 4.8 | 1.202 | 1.198 | 1.066 |
| T17–1 | 6.4 | Front | 9.0 | 5.1 | 5 | 4.4 | 1.127 | 1.003 | 0.981 |
| | | Back | 9.2 | 5.4 | 5.4 | 4.7 | 1.160 | 1.046 | 1.029 |
| T17–2 | 6.4 | Front | 9.6 | 4.2 | 4.2 | 3.8 | 1.092 | 0.861 | 0.850 |
| | | Back | 9.1 | 6.3 | 5.9 | 5.2 | 1.139 | 1.084 | 1.145 |
| T17–3 | 6.4 | Front | 9.8 | 4.4 | 4.7 | 4.0 | 1.171 | 0.936 | 0.887 |
| | | Back | 8.4 | 6.6 | 6 | 5.2 | 1.156 | 1.132 | 1.147 |
| T18–1 | 6.4 | Front | 5.5 | 6.5 | 5 | 4.2 | 1.191 | 1.179 | 0.928 |
| | | Back | 5.7 | 6.4 | 5.2 | 4.3 | 1.222 | 1.216 | 0.941 |
| T18–2 | 6.4 | Front | 5.2 | 6.9 | 5 | 4.2 | 1.204 | 1.169 | 0.918 |
| | | Back | 5.3 | 6.1 | 5.1 | 4.0 | 1.275 | 1.266 | 0.884 |
| T18–3 | 6.4 | Front | 5.7 | 7.0 | 5.1 | 4.4 | 1.154 | 1.136 | 0.977 |
| | | Back | 5.3 | 6.4 | 5.1 | 4.1 | 1.249 | 1.233 | 0.902 |
| T19–1 | 6.4 | Front | 8.1 | 6.9 | 5.4 | 5.3 | 1.028 | 1.018 | 1.161 |
| | | Back | 7.8 | 6.8 | 5.6 | 5.1 | 1.093 | 1.085 | 1.133 |
| T19–2 | 6.4 | Front | 8.8 | 7.6 | 5.8 | 5.8 | 1.008 | 1.000 | 1.271 |
| | | Back | 8.1 | 6.0 | 5.5 | 4.8 | 1.141 | 1.103 | 1.066 |
| T19–3 | 6.4 | Front | 8.7 | 7.2 | 5.6 | 5.5 | 1.010 | 0.996 | 1.226 |
| | | Back | 8.0 | 6.2 | 5.6 | 4.9 | 1.143 | 1.116 | 1.083 |
| C1–1 | 6.4 | Front | 7.2 | 5.1 | 5.5 | 4.2 | 1.322 | 1.265 | 0.920 |
| | | Back | 7.8 | 6.1 | 5.6 | 4.8 | 1.165 | 1.140 | 1.062 |
| C1–2 | 6.4 | Front | 7.3 | 5.1 | 5.5 | 4.2 | 1.316 | 1.255 | 0.924 |
| | | Back | 7.7 | 6.4 | 5.6 | 4.9 | 1.138 | 1.124 | 1.088 |
| C1–3 | 6.4 | Front | 6.7 | 5.5 | 5.5 | 4.3 | 1.294 | 1.275 | 0.940 |
| | | Back | 7.7 | 6.4 | 5.6 | 4.9 | 1.138 | 1.124 | 1.088 |
| C2–1 | 6.4 | Front | 5.8 | 6.5 | 5.5 | 4.3 | 1.271 | 1.265 | 0.956 |
| | | Back | 7.4 | 6.5 | 5.6 | 4.9 | 1.147 | 1.140 | 1.079 |
| C2–2 | 6.4 | Front | 7.7 | 5.7 | 5.5 | 4.6 | 1.201 | 1.161 | 1.012 |
| | | Back | 5.9 | 7.0 | 5.6 | 4.5 | 1.241 | 1.228 | 0.997 |
| C2–3 | 6.4 | Front | 7.3 | 5.6 | 5.5 | 4.4 | 1.238 | 1.206 | 0.982 |
| | | Back | 5.8 | 7.7 | 5.6 | 4.6 | 1.209 | 1.173 | 1.024 |
| All Specimens | | | Mean of Ratios | | | | 1.165 | 1.145 | 1.026 |
| | | | Coefficient of Variation, $V$ | | | | 0.070 | 0.077 | 0.102 |

**Table E12.2** – Weld Size Measurements from Ng *et al.* (2002) – 12.7 mm welds

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| T20–1 | 12.7 | Front | 13.4 | 14.2 | 9.8 | 9.7 | 1.006 | 1.004 | 1.085 |
| | | Back | 13.3 | 13.7 | 10.3 | 9.5 | 1.079 | 1.079 | 1.063 |
| T20–2 | 12.7 | Front | 12.8 | 13.2 | 9.2 | 9.2 | 1.001 | 1.001 | 1.023 |
| | | Back | 13.4 | 14.6 | 9.6 | 9.9 | 0.972 | 0.970 | 1.099 |
| T20–3 | 12.7 | Front | 13.3 | 14.1 | 10.1 | 9.7 | 1.044 | 1.043 | 1.078 |
| | | Back | 13.9 | 13.6 | 9.4 | 9.7 | 0.967 | 0.967 | 1.083 |
| T21–1 | 12.7 | Front | 11.3 | 14.0 | 11.1 | 8.8 | 1.262 | 1.241 | 0.979 |
| | | Back | 12.2 | 13.1 | 11.6 | 8.9 | 1.299 | 1.297 | 0.994 |
| T21–2 | 12.7 | Front | 12.2 | 13.7 | 11.3 | 9.1 | 1.240 | 1.234 | 1.015 |
| | | Back | 12.1 | 13.7 | 12.1 | 9.1 | 1.334 | 1.327 | 1.010 |
| T21–3 | 12.7 | Front | 12.1 | 13.5 | 10.9 | 9.0 | 1.210 | 1.204 | 1.004 |
| | | Back | 12.2 | 13.5 | 11.7 | 9.1 | 1.293 | 1.288 | 1.008 |
| T22–1 | 12.7 | Front | 9.4 | 10.6 | 7.8 | 7.0 | 1.109 | 1.103 | 0.783 |
| | | Back | 11.1 | 11.9 | 9.2 | 8.1 | 1.133 | 1.132 | 0.904 |
| T22–2 | 12.7 | Front | 10.3 | 10.0 | 8 | 7.2 | 1.115 | 1.115 | 0.799 |
| | | Back | 10.8 | 11.5 | 9 | 7.9 | 1.143 | 1.142 | 0.877 |
| T22–3 | 12.7 | Front | 11.1 | 10.1 | 8.4 | 7.5 | 1.124 | 1.121 | 0.832 |
| | | Back | 10.1 | 11.6 | 8.5 | 7.6 | 1.116 | 1.108 | 0.848 |
| T23–1 | 12.7 | Front | 12.6 | 12.8 | 10.2 | 9.0 | 1.136 | 1.136 | 1.000 |
| | | Back | 13.5 | 13.0 | 10 | 9.4 | 1.068 | 1.067 | 1.043 |
| T23–2 | 12.7 | Front | 12.5 | 12.7 | 10.5 | 8.9 | 1.179 | 1.179 | 0.992 |
| | | Back | 13.4 | 13.0 | 10.2 | 9.3 | 1.093 | 1.093 | 1.039 |
| T23–3 | 12.7 | Front | 12.7 | 13.3 | 10.5 | 9.2 | 1.143 | 1.142 | 1.023 |
| | | Back | 13.2 | 12.8 | 9.9 | 9.2 | 1.077 | 1.077 | 1.023 |
| T24–1 | 12.7 | Front | 11.6 | 10.9 | 8.2 | 7.9 | 1.032 | 1.031 | 0.885 |
| | | Back | 11.7 | 11.8 | 8.6 | 8.3 | 1.035 | 1.035 | 0.925 |
| T24–2 | 12.7 | Front | 12.7 | 10.5 | 8.4 | 8.1 | 1.038 | 1.024 | 0.901 |
| | | Back | 12.0 | 11.4 | 8.9 | 8.3 | 1.077 | 1.076 | 0.920 |
| T24–3 | 12.7 | Front | 13.4 | 10.7 | 8.4 | 8.4 | 1.005 | 0.986 | 0.931 |
| | | Back | 12.0 | 11.1 | 8.2 | 8.1 | 1.006 | 1.004 | 0.908 |
| T25–1 | 12.7 | Front | 13.8 | 11.4 | 9.5 | 8.8 | 1.081 | 1.066 | 0.979 |
| | | Back | 14.8 | 10.7 | 10.2 | 8.7 | 1.176 | 1.132 | 0.966 |
| T25–2 | 12.7 | Front | 12.3 | 11.8 | 9.1 | 8.5 | 1.069 | 1.068 | 0.948 |
| | | Back | 12.4 | 11.4 | 9.4 | 8.4 | 1.120 | 1.117 | 0.935 |
| T25–3 | 12.7 | Front | 13.7 | 11.7 | 9.7 | 8.9 | 1.090 | 1.080 | 0.991 |
| | | Back | 13.3 | 10.9 | 9.5 | 8.4 | 1.127 | 1.111 | 0.939 |
| T26–1 | 12.7 | Front | 12.4 | 11.6 | 9.5 | 8.5 | 1.121 | 1.120 | 0.943 |
| | | Back | 13.2 | 10.6 | 9 | 8.3 | 1.089 | 1.070 | 0.920 |
| T26–2 | 12.7 | Front | 12.4 | 11.9 | 9.5 | 8.6 | 1.106 | 1.106 | 0.956 |
| | | Back | 12.7 | 11.2 | 9.2 | 8.4 | 1.095 | 1.089 | 0.936 |
| T26–3 | 12.7 | Front | 13.0 | 11.7 | 9.3 | 8.7 | 1.069 | 1.065 | 0.969 |
| | | Back | 13.0 | 11.6 | 9.3 | 8.7 | 1.074 | 1.069 | 0.964 |
| T27–1 | 12.7 | Front | 12.8 | 11.4 | 8 | 8.5 | 0.940 | 0.935 | 0.948 |
| | | Back | 11.6 | 12.1 | 8.4 | 8.4 | 1.003 | 1.003 | 0.933 |

**Table E12.2 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| T27–2 | 12.7 | Front | 12.5 | 11.8 | 8.3 | 8.6 | 0.967 | 0.966 | 0.956 |
| | | Back | 11.8 | 12.0 | 8.3 | 8.4 | 0.986 | 0.987 | 0.937 |
| T27–3 | 12.7 | Front | 12.2 | 12.1 | 8.4 | 8.6 | 0.978 | 0.978 | 0.957 |
| | | Back | 11.6 | 11.8 | 8.4 | 8.3 | 1.015 | 1.015 | 0.921 |
| T28–1 | 12.7 | Front | 13.8 | 10.6 | 8.9 | 8.4 | 1.059 | 1.032 | 0.936 |
| | | Back | 12.5 | 10.7 | 8.3 | 8.1 | 1.021 | 1.012 | 0.905 |
| T28–2 | 12.7 | Front | 13.3 | 10.7 | 9.1 | 8.3 | 1.092 | 1.073 | 0.929 |
| | | Back | 12.2 | 10.8 | 8.3 | 8.1 | 1.026 | 1.021 | 0.901 |
| T28–3 | 12.7 | Front | 13.0 | 11.2 | 9 | 8.5 | 1.061 | 1.052 | 0.945 |
| | | Back | 12.9 | 10.9 | 8.4 | 8.3 | 1.009 | 0.998 | 0.927 |
| T29–1 | 12.7 | Front | 12.7 | 12.0 | 10.2 | 8.7 | 1.169 | 1.168 | 0.971 |
| | | Back | 16.3 | 12.6 | 9.3 | 10.0 | 0.933 | 0.910 | 1.110 |
| T29–2 | 12.7 | Front | 13.4 | 12.8 | 10.3 | 9.3 | 1.113 | 1.112 | 1.031 |
| | | Back | 16.8 | 12.2 | 9.3 | 9.9 | 0.942 | 0.907 | 1.099 |
| T29–3 | 12.7 | Front | 16.0 | 12.0 | 9.7 | 9.6 | 1.010 | 0.980 | 1.069 |
| | | Back | 13.4 | 13.7 | 10.7 | 9.6 | 1.117 | 1.117 | 1.067 |
| T30–1 | 12.7 | Front | 12.7 | 11.2 | 8.8 | 8.4 | 1.048 | 1.042 | 0.936 |
| | | Back | 13.1 | 10.3 | 8.5 | 8.1 | 1.050 | 1.028 | 0.902 |
| T30–2 | 12.7 | Front | 12.6 | 10.3 | 8.8 | 8.0 | 1.104 | 1.087 | 0.888 |
| | | Back | 13.7 | 9.6 | 8.5 | 7.9 | 1.081 | 1.032 | 0.876 |
| T30–3 | 12.7 | Front | 12.3 | 10.4 | 8.2 | 7.9 | 1.033 | 1.022 | 0.884 |
| | | Back | 13.2 | 10.3 | 8.3 | 8.1 | 1.022 | 0.999 | 0.904 |
| T31–1 | 12.7 | Front | 11.5 | 10.7 | 8.7 | 7.8 | 1.111 | 1.109 | 0.872 |
| | | Back | 10.5 | 12.4 | 9.4 | 8.0 | 1.173 | 1.161 | 0.892 |
| T31–2 | 12.7 | Front | 11.4 | 11.8 | 8.8 | 8.2 | 1.073 | 1.073 | 0.913 |
| | | Back | 10.7 | 12.1 | 9.3 | 8.0 | 1.160 | 1.154 | 0.893 |
| T31–3 | 12.7 | Front | 11.4 | 12.4 | 9.4 | 8.4 | 1.120 | 1.117 | 0.935 |
| | | Back | 10.3 | 11.4 | 9.3 | 7.6 | 1.217 | 1.212 | 0.851 |
| T32–1 | 12.7 | Front | 12.3 | 11.2 | 8.8 | 8.3 | 1.063 | 1.059 | 0.922 |
| | | Back | 12.2 | 12.7 | 8.9 | 8.8 | 1.012 | 1.011 | 0.980 |
| T32–2 | 12.7 | Front | 11.4 | 11.7 | 9.1 | 8.2 | 1.115 | 1.114 | 0.909 |
| | | Back | 12.1 | 12.7 | 9 | 8.8 | 1.027 | 1.027 | 0.976 |
| T32–3 | 12.7 | Front | 10.5 | 12.9 | 8.7 | 8.1 | 1.068 | 1.052 | 0.907 |
| | | Back | 12.2 | 11.8 | 9 | 8.5 | 1.061 | 1.061 | 0.945 |
| All Specimens | | | Mean of Ratios | | | | 1.084 | 1.076 | 0.954 |
| | | | Coefficient of Variation, $V$ | | | | 0.076 | 0.077 | 0.073 |

**Table E12.3** – Weld Size Measurements from Deng *et al.* (2003) – 12.7 mm welds

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| F1–1 | 12.7 | Front | 11.3 | 10.8 | 8.7 | 7.8 | 1.114 | 1.114 | 0.870 |
| | | Back | 11.8 | 11.0 | 8.6 | 8.0 | 1.069 | 1.067 | 0.896 |
| F1–2 | 12.7 | Front | 9.9 | 9.5 | 7.1 | 6.9 | 1.036 | 1.035 | 0.763 |
| | | Back | 10.9 | 9.7 | 7.4 | 7.2 | 1.021 | 1.016 | 0.807 |
| F1–3 | 12.7 | Front | 9.5 | 10.0 | 8.0 | 6.9 | 1.162 | 1.161 | 0.767 |
| | | Back | 11.1 | 10.4 | 8.3 | 7.6 | 1.094 | 1.092 | 0.845 |
| F2–1 | 12.7 | Front | 9.5 | 10.1 | 7.6 | 6.9 | 1.098 | 1.097 | 0.771 |
| | | Back | 9.9 | 11.4 | 7.6 | 7.5 | 1.017 | 1.009 | 0.832 |
| F2–2 | 12.7 | Front | 10.7 | 11.2 | 8.1 | 7.7 | 1.047 | 1.046 | 0.862 |
| | | Back | 10.3 | 11.0 | 8.2 | 7.5 | 1.091 | 1.089 | 0.837 |
| F2–3 | 12.7 | Front | 9.3 | 11.0 | 7.5 | 7.1 | 1.056 | 1.045 | 0.791 |
| | | Back | 11.0 | 11.0 | 8.1 | 7.8 | 1.041 | 1.042 | 0.866 |
| F3–1 | 12.7 | Front | 10.0 | 12.3 | 8.8 | 7.8 | 1.134 | 1.116 | 0.864 |
| | | Back | 10.5 | 13.4 | 8.8 | 8.3 | 1.065 | 1.042 | 0.920 |
| F3–2 | 12.7 | Front | 10.3 | 10.7 | 7.6 | 7.4 | 1.024 | 1.024 | 0.826 |
| | | Back | 9.5 | 11.5 | 7.6 | 7.3 | 1.038 | 1.024 | 0.816 |
| F3–3 | 12.7 | Front | 9.2 | 12.6 | 7.6 | 7.4 | 1.023 | 0.986 | 0.828 |
| | | Back | 9.5 | 13.0 | 8.6 | 7.7 | 1.121 | 1.081 | 0.854 |
| L1–1 | 12.7 | Weld 1 | 10.6 | 11.4 | 5.9 | 7.8 | 0.760 | 0.759 | 0.865 |
| | | Weld 2 | 8.7 | 9.4 | 7.2 | 6.4 | 1.128 | 1.125 | 0.711 |
| | | Weld 3 | 10.5 | 10.6 | 8.4 | 7.5 | 1.126 | 1.126 | 0.831 |
| | | Weld 4 | 10.0 | 11.0 | 7.6 | 7.4 | 1.027 | 1.024 | 0.824 |
| L1–2 | 12.7 | Weld 1 | 11.3 | 11.5 | 7.8 | 8.1 | 0.968 | 0.968 | 0.898 |
| | | Weld 2 | 11.7 | 10.4 | 7.8 | 7.8 | 1.003 | 0.998 | 0.866 |
| | | Weld 3 | 11.0 | 9.6 | 7.6 | 7.2 | 1.051 | 1.044 | 0.806 |
| | | Weld 4 | 10.9 | 9.4 | 7.4 | 7.1 | 1.040 | 1.031 | 0.793 |
| L1–3 | 12.7 | Weld 1 | 10.8 | 11.5 | 8.0 | 7.9 | 1.016 | 1.015 | 0.877 |
| | | Weld 2 | 9.4 | 10.7 | 6.9 | 7.1 | 0.977 | 0.971 | 0.787 |
| | | Weld 3 | 10.8 | 10.1 | 7.6 | 7.4 | 1.030 | 1.029 | 0.822 |
| | | Weld 4 | 10.3 | 10.4 | 7.3 | 7.3 | 0.997 | 0.998 | 0.815 |
| L2–1 | 12.7 | Weld 1 | 10.9 | 12.0 | 9.2 | 8.1 | 1.140 | 1.136 | 0.899 |
| | | Weld 2 | 10.7 | 11.4 | 8.2 | 7.8 | 1.051 | 1.050 | 0.869 |
| | | Weld 3 | 10.8 | 11.3 | 8.0 | 7.8 | 1.025 | 1.024 | 0.870 |
| | | Weld 4 | 11.6 | 11.2 | 7.3 | 8.1 | 0.906 | 0.906 | 0.897 |
| L2–2 | 12.7 | Weld 1 | 10.3 | 11.0 | 6.9 | 7.5 | 0.918 | 0.916 | 0.837 |
| | | Weld 2 | 10.0 | 10.1 | 6.8 | 7.1 | 0.957 | 0.957 | 0.791 |
| | | Weld 3 | 12.3 | 11.0 | 7.7 | 8.2 | 0.939 | 0.935 | 0.913 |
| | | Weld 4 | 9.8 | 11.6 | 6.5 | 7.5 | 0.868 | 0.859 | 0.834 |
| L2–3 | 12.7 | Weld 1 | 11.2 | 11.9 | 9.0 | 8.2 | 1.104 | 1.102 | 0.908 |
| | | Weld 2 | 9.8 | 11.2 | 7.3 | 7.4 | 0.990 | 0.983 | 0.821 |
| | | Weld 3 | 10.5 | 11.8 | 8.2 | 7.8 | 1.045 | 1.040 | 0.874 |
| | | Weld 4 | 10.5 | 11.0 | 7.9 | 7.6 | 1.040 | 1.039 | 0.846 |

**Table E12.3 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| L3–1 | 12.7 | Weld 1 | 10.0 | 11.9 | 9.1 | 7.7 | 1.189 | 1.175 | 0.853 |
| | | Weld 2 | 10.3 | 10.8 | 9.7 | 7.5 | 1.301 | 1.300 | 0.830 |
| | | Weld 3 | 9.8 | 10.7 | 8.0 | 7.2 | 1.107 | 1.104 | 0.805 |
| | | Weld 4 | 9.0 | 10.7 | 8.2 | 6.9 | 1.191 | 1.177 | 0.767 |
| L3–2 | 12.7 | Weld 1 | 9.5 | 12.2 | 7.6 | 7.5 | 1.014 | 0.991 | 0.835 |
| | | Weld 2 | 9.7 | 11.4 | 6.8 | 7.4 | 0.920 | 0.912 | 0.823 |
| | | Weld 3 | 9.6 | 12.0 | 8.3 | 7.5 | 1.107 | 1.087 | 0.835 |
| | | Weld 4 | 10.0 | 11.1 | 7.4 | 7.4 | 0.996 | 0.992 | 0.827 |
| L3–3 | 12.7 | Weld 1 | 9.3 | 11.3 | 7.5 | 7.2 | 1.044 | 1.030 | 0.800 |
| | | Weld 2 | 11.7 | 11.5 | 8.9 | 8.2 | 1.085 | 1.085 | 0.913 |
| | | Weld 3 | 10.7 | 10.2 | 8.6 | 7.4 | 1.165 | 1.164 | 0.822 |
| | | Weld 4 | 9.7 | 9.8 | 8.2 | 6.9 | 1.189 | 1.190 | 0.768 |
| All Specimens | | | Mean of Ratios | | | | 1.049 | 1.043 | 0.836 |
| | | | Coefficient of Variation, $V$ | | | | 0.085 | 0.086 | 0.053 |

**Table E12.4** – Weld Size Measurements from Callele *et al.* (2005) – 7.9 mm welds

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| TFa–1 | 7.9 | Front–1 | 9.4 | 8.7 | 7.6 | 6.4 | 1.190 | 1.188 | 1.138 |
| | | Front–2 | 9.2 | 9.2 | 7.7 | 6.5 | 1.190 | 1.190 | 1.159 |
| | | Front–3 | 9.0 | 8.8 | 7.9 | 6.3 | 1.252 | 1.252 | 1.121 |
| | | Back–1 | 8.4 | 7.5 | 5.8 | 5.6 | 1.037 | 1.032 | 0.997 |
| | | Back–2 | 9.6 | 8.2 | 6.2 | 6.2 | 0.998 | 0.989 | 1.111 |
| | | Back–3 | 9.1 | 8.4 | 6.8 | 6.2 | 1.094 | 1.091 | 1.100 |
| TFa–2 | 7.9 | Front–1 | 9.4 | 8.2 | 7.1 | 6.2 | 1.149 | 1.141 | 1.101 |
| | | Front–2 | 9.5 | 8.0 | 6.3 | 6.1 | 1.036 | 1.025 | 1.090 |
| | | Front–3 | 9.6 | 8.8 | 7.0 | 6.5 | 1.083 | 1.080 | 1.156 |
| | | Back–1 | 8.4 | 7.5 | 6.5 | 5.6 | 1.162 | 1.156 | 0.997 |
| | | Back–2 | 8.9 | 7.7 | 6.1 | 5.8 | 1.051 | 1.043 | 1.038 |
| | | Back–3 | 9.0 | 7.1 | 5.8 | 5.6 | 1.040 | 1.019 | 0.993 |
| TFa–3 | 7.9 | Front–1 | 9.0 | 8.3 | 7.1 | 6.1 | 1.155 | 1.153 | 1.087 |
| | | Front–2 | 9.0 | 8.5 | 7.0 | 6.2 | 1.133 | 1.132 | 1.101 |
| | | Front–3 | 8.8 | 8.1 | 7.7 | 6.0 | 1.288 | 1.285 | 1.062 |
| | | Back–1 | 8.9 | 8.1 | 6.3 | 6.0 | 1.043 | 1.040 | 1.067 |
| | | Back–2 | 9.2 | 7.7 | 6.6 | 5.9 | 1.118 | 1.105 | 1.052 |
| | | Back–3 | 9.1 | 8.2 | 6.4 | 6.1 | 1.051 | 1.047 | 1.086 |

**Table E12.4 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| TFa–4 | 7.9 | Front–1 | 9.3 | 9.6 | 7.9 | 6.7 | 1.183 | 1.182 | 1.190 |
| | | Front–2 | 9.6 | 9.9 | 8.1 | 6.9 | 1.178 | 1.178 | 1.228 |
| | | Front–3 | 8.5 | 9.3 | 7.3 | 6.3 | 1.160 | 1.156 | 1.118 |
| | | Back–1 | 8.5 | 9.4 | 7.4 | 6.3 | 1.170 | 1.166 | 1.123 |
| | | Back–2 | 8.8 | 9.2 | 7.5 | 6.4 | 1.179 | 1.179 | 1.133 |
| | | Back–3 | 8.4 | 7.4 | 6.2 | 5.6 | 1.121 | 1.115 | 0.989 |
| TL50a–1 | 7.9 | Front–1 | 9.6 | 7.8 | 6.2 | 6.1 | 1.016 | 1.000 | 1.084 |
| | | Front–2 | 10.7 | 8.3 | 7.1 | 6.6 | 1.077 | 1.051 | 1.174 |
| | | Front–3 | 9.2 | 8.4 | 6.6 | 6.2 | 1.056 | 1.053 | 1.111 |
| | | Back–1 | 8.4 | 7.4 | 5.9 | 5.6 | 1.067 | 1.061 | 0.994 |
| | | Back–2 | 10.7 | 8.2 | 7.1 | 6.5 | 1.097 | 1.069 | 1.165 |
| | | Back–3 | 8.6 | 8.5 | 6.8 | 6.0 | 1.117 | 1.117 | 1.082 |
| TL50a–2 | 7.9 | Front–1 | 9.6 | 7.8 | 6.1 | 6.1 | 1.008 | 0.992 | 1.084 |
| | | Front–2 | 10.7 | 8.3 | 7.0 | 6.6 | 1.070 | 1.045 | 1.174 |
| | | Front–3 | 9.8 | 8.2 | 6.3 | 6.3 | 0.994 | 0.982 | 1.126 |
| | | Back–1 | 9.3 | 8.5 | 6.9 | 6.3 | 1.096 | 1.093 | 1.123 |
| | | Back–2 | 11.3 | 8.2 | 7.2 | 6.6 | 1.088 | 1.047 | 1.188 |
| | | Back–3 | 10.0 | 8.4 | 7.0 | 6.4 | 1.081 | 1.069 | 1.152 |
| TL50a–3 | 7.9 | Front–1 | 8.4 | 7.6 | 6.3 | 5.6 | 1.122 | 1.118 | 1.009 |
| | | Front–2 | 10.7 | 8.2 | 7.1 | 6.5 | 1.094 | 1.066 | 1.165 |
| | | Front–3 | 9.7 | 8.0 | 7.0 | 6.2 | 1.126 | 1.111 | 1.105 |
| | | Back–1 | 9.0 | 9.2 | 6.2 | 6.4 | 0.960 | 0.960 | 1.152 |
| | | Back–2 | 10.7 | 8.2 | 7.3 | 6.5 | 1.128 | 1.099 | 1.165 |
| | | Back–3 | 9.7 | 8.0 | 6.7 | 6.2 | 1.082 | 1.067 | 1.105 |
| TL50a–4 | 7.9 | Front–1 | 10.0 | 8.5 | 6.8 | 6.5 | 1.054 | 1.044 | 1.160 |
| | | Front–2 | 11.8 | 9.1 | 7.6 | 7.2 | 1.052 | 1.026 | 1.290 |
| | | Front–3 | 9.1 | 9.6 | 7.2 | 6.6 | 1.090 | 1.089 | 1.182 |
| | | Back–1 | 10.8 | 8.7 | 7.3 | 6.8 | 1.077 | 1.059 | 1.213 |
| | | Back–2 | 12.3 | 7.9 | 7.4 | 6.6 | 1.119 | 1.042 | 1.190 |
| | | Back–3 | 10.0 | 9.5 | 8.1 | 6.9 | 1.180 | 1.179 | 1.233 |
| All Specimens | | | Mean of Ratios | | | | 1.102 | 1.091 | 1.118 |
| | | | Coefficient of Variation, $V$ | | | | 0.061 | 0.065 | 0.061 |

**Table E12.5** – Weld Measurements of Specimens of 12.7 mm Weld from Callele *et al.* (2005)

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| TF–1 | 12.7 | Front–1 | 12.9 | 10.5 | 8.4 | 8.1 | 1.028 | 1.012 | 0.907 |
| | | Front–2 | 14.2 | 11.6 | 8.8 | 9.0 | 0.980 | 0.965 | 1.001 |
| | | Front–3 | 14.4 | 11.0 | 8.4 | 8.7 | 0.964 | 0.938 | 0.974 |
| | | Back–1 | 14.4 | 11.6 | 9.6 | 9.0 | 1.063 | 1.045 | 1.006 |
| | | Back–2 | 13.7 | 12.3 | 9.5 | 9.2 | 1.036 | 1.031 | 1.019 |
| | | Back–3 | 14.9 | 13.2 | 10.4 | 9.9 | 1.050 | 1.044 | 1.100 |
| TF–2 | 12.7 | Front–1 | 12.4 | 13.6 | 9.6 | 9.2 | 1.048 | 1.045 | 1.021 |
| | | Front–2 | 15.0 | 13.6 | 10.3 | 10.1 | 1.020 | 1.017 | 1.122 |
| | | Front–3 | 13.2 | 13.7 | 9.5 | 9.5 | 0.999 | 0.999 | 1.059 |
| | | Back–1 | 12.5 | 12.6 | 9.7 | 8.9 | 1.090 | 1.090 | 0.988 |
| | | Back–2 | 13.6 | 12.7 | 9.9 | 9.3 | 1.062 | 1.061 | 1.034 |
| | | Back–3 | 13.5 | 12.5 | 9.4 | 9.2 | 1.025 | 1.023 | 1.022 |
| TF–3 | 12.7 | Front–1 | 13.9 | 12.1 | 8.8 | 9.1 | 0.959 | 0.952 | 1.016 |
| | | Front–2 | 13.5 | 11.8 | 8.7 | 8.9 | 0.981 | 0.975 | 0.989 |
| | | Front–3 | 13.2 | 11.2 | 8.7 | 8.5 | 1.013 | 1.003 | 0.951 |
| | | Back–1 | 12.2 | 12.0 | 9.0 | 8.6 | 1.055 | 1.055 | 0.953 |
| | | Back–2 | 13.1 | 11.6 | 8.8 | 8.7 | 1.011 | 1.006 | 0.967 |
| | | Back–3 | 12.4 | 11.3 | 8.3 | 8.4 | 0.988 | 0.985 | 0.930 |
| TF–4 | 12.7 | Front–1 | 14.3 | 11.7 | 9.2 | 9.1 | 1.019 | 1.004 | 1.009 |
| | | Front–2 | 17.1 | 11.7 | 8.6 | 9.7 | 0.893 | 0.847 | 1.075 |
| | | Front–3 | 13.7 | 10.8 | 8.8 | 8.5 | 1.041 | 1.019 | 0.945 |
| | | Back–1 | 14.8 | 12.5 | 9.7 | 9.5 | 1.013 | 1.003 | 1.064 |
| | | Back–2 | 16.8 | 12.6 | 9.8 | 10.1 | 0.972 | 0.943 | 1.123 |
| | | Back–3 | 15.4 | 12.5 | 9.5 | 9.7 | 0.981 | 0.966 | 1.081 |
| TL50–1 | 12.7 | Front–1 | 15.7 | 11.5 | 8.0 | 9.3 | 0.862 | 0.832 | 1.033 |
| | | Front–2 | 16.4 | 12.3 | 11.9 | 9.8 | 1.207 | 1.171 | 1.096 |
| | | Front–3 | 12.9 | 12.9 | 9.9 | 9.1 | 1.085 | 1.085 | 1.016 |
| | | Back–1 | 14.1 | 10.1 | 7.7 | 8.2 | 0.941 | 0.903 | 0.914 |
| | | Back–2 | 16.0 | 11.0 | 8.5 | 9.1 | 0.940 | 0.893 | 1.010 |
| | | Back–3 | 12.8 | 11.6 | 9.2 | 8.6 | 1.065 | 1.061 | 0.957 |
| TL50–2 | 12.7 | Front–1 | 13.7 | 12.2 | 9.0 | 9.1 | 0.985 | 0.980 | 1.015 |
| | | Front–2 | 15.2 | 11.9 | 9.4 | 9.4 | 1.007 | 0.985 | 1.044 |
| | | Front–3 | 14.9 | 12.2 | 10.7 | 9.4 | 1.131 | 1.114 | 1.051 |
| | | Back–1 | 13.5 | 10.3 | 8.9 | 8.2 | 1.081 | 1.052 | 0.912 |
| | | Back–2 | 13.5 | 11.9 | 9.2 | 8.9 | 1.035 | 1.029 | 0.994 |
| | | Back–3 | 13.1 | 11.9 | 9.2 | 8.8 | 1.047 | 1.044 | 0.981 |
| TL50–3 | 12.7 | Front–1 | 14.2 | 10.7 | 8.3 | 8.5 | 0.974 | 0.946 | 0.952 |
| | | Front–2 | 15.3 | 12.8 | 10.3 | 9.8 | 1.049 | 1.037 | 1.093 |
| | | Front–3 | 12.0 | 12.9 | 9.1 | 8.8 | 1.030 | 1.028 | 0.979 |
| | | Back–1 | 14.0 | 11.1 | 8.9 | 8.7 | 1.017 | 0.997 | 0.969 |
| | | Back–2 | 15.3 | 11.8 | 9.6 | 9.3 | 1.030 | 1.004 | 1.041 |
| | | Back–3 | 12.8 | 9.8 | 8.0 | 7.8 | 1.025 | 0.998 | 0.867 |

**Table E12.5 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| TL50–4 | 12.7 | Front–1 | 17.1 | 10.2 | 9.2 | 8.8 | 1.050 | 0.953 | 0.976 |
| | | Front–2 | 18.3 | 11.0 | 9.8 | 9.4 | 1.039 | 0.946 | 1.050 |
| | | Front–3 | 13.7 | 11.8 | 9.9 | 8.9 | 1.107 | 1.098 | 0.996 |
| | | Back–1 | 13.1 | 11.3 | 9.3 | 8.6 | 1.090 | 1.081 | 0.953 |
| | | Back–2 | 15.8 | 11.2 | 10.6 | 9.1 | 1.156 | 1.106 | 1.018 |
| | | Back–3 | 14.6 | 11.8 | 11.1 | 9.2 | 1.210 | 1.189 | 1.022 |
| TL100–1 | 12.7 | Front–1 | 13.9 | 12.9 | 10.5 | 9.5 | 1.113 | 1.111 | 1.053 |
| | | Front–2 | 17.1 | 12.4 | 11.3 | 10.0 | 1.126 | 1.084 | 1.118 |
| | | Front–3 | 15.2 | 13.9 | 11.3 | 10.3 | 1.099 | 1.096 | 1.142 |
| | | Back–1 | 14.6 | 12.9 | 10.7 | 9.7 | 1.106 | 1.099 | 1.077 |
| | | Back–2 | 17.5 | 13.0 | 11.5 | 10.4 | 1.098 | 1.063 | 1.162 |
| | | Back–3 | 16.4 | 13.9 | 11.9 | 10.6 | 1.119 | 1.108 | 1.181 |
| TL100–2 | 12.7 | Front–1 | 14.1 | 10.6 | 9.2 | 8.5 | 1.083 | 1.051 | 0.944 |
| | | Front–2 | 14.6 | 11.0 | 9.2 | 8.8 | 1.045 | 1.014 | 0.978 |
| | | Front–3 | 13.5 | 10.6 | 10.1 | 8.3 | 1.207 | 1.181 | 0.929 |
| | | Back–1 | 15.4 | 12.6 | 10.9 | 9.8 | 1.116 | 1.100 | 1.086 |
| | | Back–2 | 16.7 | 11.9 | 10.6 | 9.7 | 1.098 | 1.052 | 1.079 |
| | | Back–3 | 15.3 | 11.5 | 10.8 | 9.2 | 1.172 | 1.137 | 1.024 |
| TL100–3 | 12.7 | Front–1 | 13.8 | 12.5 | 10.3 | 9.3 | 1.109 | 1.105 | 1.032 |
| | | Front–2 | 16.8 | 12.6 | 10.6 | 10.1 | 1.054 | 1.022 | 1.123 |
| | | Front–3 | 13.7 | 13.0 | 10.7 | 9.4 | 1.137 | 1.136 | 1.050 |
| | | Back–1 | 12.5 | 11.5 | 8.3 | 8.5 | 0.975 | 0.972 | 0.943 |
| | | Back–2 | 15.7 | 10.8 | 8.6 | 8.9 | 0.962 | 0.914 | 0.991 |
| | | Back–3 | 14.0 | 10.3 | 7.8 | 8.3 | 0.937 | 0.905 | 0.924 |
| TL100SP–1 | 12.7 | Front–1 | 12.9 | 10.6 | 9.8 | 8.2 | 1.200 | 1.183 | 0.912 |
| | | Front–2 | 12.2 | 9.3 | 9.0 | 7.4 | 1.214 | 1.182 | 0.824 |
| | | Front–3 | 11.9 | 9.7 | 8.5 | 7.5 | 1.126 | 1.108 | 0.837 |
| | | Back–1 | 11.7 | 9.3 | 9.0 | 7.3 | 1.229 | 1.206 | 0.811 |
| | | Back–2 | 12.8 | 9.7 | 9.1 | 7.7 | 1.172 | 1.139 | 0.861 |
| | | Back–3 | 13.9 | 11.7 | 10.9 | 9.0 | 1.212 | 1.199 | 0.997 |

**Table E12.5 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| TL100SP–2 | 12.7 | Front–1 | 11.9 | 9.9 | 8.3 | 7.6 | 1.086 | 1.072 | 0.848 |
| | | Front–2 | 12.2 | 10.1 | 8.4 | 7.8 | 1.082 | 1.068 | 0.866 |
| | | Front–3 | 14.0 | 11.6 | 9.8 | 8.9 | 1.100 | 1.086 | 0.995 |
| | | Back–1 | 11.9 | 10.8 | 8.6 | 8.0 | 1.071 | 1.067 | 0.891 |
| | | Back–2 | 13.9 | 9.7 | 8.9 | 8.0 | 1.124 | 1.072 | 0.886 |
| | | Back–3 | 14.1 | 10.7 | 9.4 | 8.5 | 1.104 | 1.074 | 0.949 |
| TL100SP–3 | 12.7 | Front–1 | 14.3 | 10.0 | 8.5 | 8.2 | 1.033 | 0.985 | 0.913 |
| | | Front–2 | 13.5 | 10.9 | 8.4 | 8.5 | 0.993 | 0.976 | 0.945 |
| | | Front–3 | 12.8 | 10.6 | 8.7 | 8.2 | 1.070 | 1.056 | 0.909 |
| | | Back–1 | 13.4 | 9.6 | 8.8 | 7.8 | 1.132 | 1.087 | 0.869 |
| | | Back–2 | 13.7 | 9.4 | 8.9 | 7.8 | 1.143 | 1.085 | 0.863 |
| | | Back–3 | 13.9 | 10.3 | 8.9 | 8.3 | 1.078 | 1.043 | 0.922 |
| TL100D–1 | 12.7 | Front–1 | 12.4 | 12.1 | 9.8 | 8.7 | 1.133 | 1.133 | 0.966 |
| | | Front–2 | 13.0 | 10.9 | 9.5 | 8.3 | 1.141 | 1.128 | 0.927 |
| | | Front–3 | 13.0 | 10.4 | 8.9 | 8.1 | 1.101 | 1.081 | 0.904 |
| | | Back–1 | 14.1 | 11.3 | 10.7 | 8.8 | 1.206 | 1.186 | 0.984 |
| | | Back–2 | 14.6 | 12.6 | 10.3 | 9.5 | 1.081 | 1.073 | 1.058 |
| | | Back–3 | 13.5 | 11.7 | 9.7 | 8.8 | 1.100 | 1.092 | 0.982 |
| TL100D–2 | 12.7 | Front–1 | 12.8 | 11.4 | 9.2 | 8.5 | 1.076 | 1.070 | 0.948 |
| | | Front–2 | 12.3 | 11.3 | 8.8 | 8.3 | 1.061 | 1.058 | 0.927 |
| | | Front–3 | 13.3 | 9.5 | 8.1 | 7.7 | 1.045 | 1.002 | 0.861 |
| | | Back–1 | 13.4 | 11.7 | 9.6 | 8.8 | 1.093 | 1.085 | 0.982 |
| | | Back–2 | 13.9 | 11.7 | 10.0 | 9.0 | 1.117 | 1.105 | 0.997 |
| | | Back–3 | 12.7 | 11.8 | 8.3 | 8.6 | 0.956 | 0.954 | 0.963 |
| TL100D–3 | 12.7 | Front–1 | 14.4 | 13.6 | 10.3 | 9.9 | 1.042 | 1.041 | 1.101 |
| | | Front–2 | 14.0 | 13.1 | 9.7 | 9.6 | 1.014 | 1.013 | 1.065 |
| | | Front–3 | 15.3 | 13.7 | 9.6 | 10.2 | 0.937 | 0.933 | 1.137 |
| | | Back–1 | 15.6 | 13.8 | 11.0 | 10.3 | 1.066 | 1.060 | 1.151 |
| | | Back–2 | 14.3 | 11.8 | 10.3 | 9.1 | 1.129 | 1.114 | 1.014 |
| | | Back–3 | 15.6 | 12.5 | 9.8 | 9.8 | 1.003 | 0.985 | 1.086 |
| TL50D–1 | 12.7 | Front–1 | 15.5 | 12.4 | 10.4 | 9.7 | 1.074 | 1.054 | 1.078 |
| | | Front–2 | 13.8 | 12.6 | 11.1 | 9.3 | 1.195 | 1.192 | 1.036 |
| | | Front–3 | 13.5 | 13.3 | 10.7 | 9.5 | 1.127 | 1.127 | 1.055 |
| | | Back–1 | 15.2 | 13.5 | 11.0 | 10.1 | 1.085 | 1.079 | 1.124 |
| | | Back–2 | 14.3 | 14.0 | 11.4 | 10.0 | 1.142 | 1.142 | 1.114 |
| | | Back–3 | 13.4 | 13.1 | 9.6 | 9.4 | 1.028 | 1.028 | 1.043 |
| TL50D–2 | 12.7 | Front–1 | 12.4 | 13.5 | 10.8 | 9.1 | 1.185 | 1.182 | 1.017 |
| | | Front–2 | 14.0 | 12.2 | 10.0 | 9.2 | 1.089 | 1.082 | 1.024 |
| | | Front–3 | 13.0 | 13.3 | 10.4 | 9.3 | 1.113 | 1.113 | 1.035 |
| | | Back–1 | 15.0 | 13.4 | 11.5 | 10.0 | 1.153 | 1.148 | 1.113 |
| | | Back–2 | 15.4 | 12.7 | 11.2 | 9.8 | 1.141 | 1.126 | 1.091 |
| | | Back–3 | 14.2 | 12.9 | 10.3 | 9.5 | 1.079 | 1.075 | 1.063 |

**Table E12.5 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| TL50D–3 | 12.7 | Front–1 | 12.2 | 14.1 | 10.1 | 9.2 | 1.097 | 1.089 | 1.028 |
| | | Front–2 | 16.7 | 11.8 | 10.0 | 9.6 | 1.038 | 0.993 | 1.073 |
| | | Front–3 | 15.4 | 11.6 | 9.6 | 9.3 | 1.031 | 1.001 | 1.032 |
| | | Back–1 | 16.9 | 12.7 | 10.4 | 10.2 | 1.027 | 0.996 | 1.131 |
| | | Back–2 | 14.9 | 10.5 | 8.9 | 8.6 | 1.042 | 0.996 | 0.956 |
| | | Back–3 | 14.4 | 10.8 | 8.9 | 8.6 | 1.033 | 1.002 | 0.962 |
| L100–1 | 12.7 | Front–1 | 12.9 | 12.2 | 9.8 | 8.9 | 1.106 | 1.104 | 0.987 |
| | | Front–2 | 12.3 | 11.3 | 9.7 | 8.3 | 1.166 | 1.163 | 0.927 |
| | | Back–3 | 12.3 | 11.6 | 9.8 | 8.4 | 1.161 | 1.160 | 0.940 |
| | | Back–4 | 12.9 | 12.0 | 9.8 | 8.8 | 1.115 | 1.113 | 0.979 |
| L100–2 | 12.7 | Front–1 | 14.7 | 12.6 | 11.0 | 9.6 | 1.150 | 1.140 | 1.065 |
| | | Front–2 | 14.2 | 10.9 | 10.9 | 8.6 | 1.261 | 1.228 | 0.963 |
| | | Back–3 | 13.1 | 11.7 | 10.6 | 8.7 | 1.215 | 1.209 | 0.972 |
| | | Back–4 | 13.8 | 10.6 | 9.1 | 8.4 | 1.083 | 1.055 | 0.936 |
| L100–3 | 12.7 | Front–1 | 13.4 | 12.8 | 10.7 | 9.3 | 1.156 | 1.155 | 1.031 |
| | | Front–2 | 13.7 | 12.7 | 11.2 | 9.3 | 1.203 | 1.200 | 1.037 |
| | | Back–3 | 12.3 | 13.0 | 10.9 | 8.9 | 1.220 | 1.219 | 0.995 |
| | | Back–4 | 13.1 | 12.9 | 11.1 | 9.2 | 1.208 | 1.208 | 1.024 |
| L100–4 | 12.7 | Front–1 | 12.3 | 8.9 | 9.3 | 7.2 | 1.290 | 1.241 | 0.803 |
| | | Front–2 | 12.6 | 9.7 | 9.5 | 7.7 | 1.236 | 1.205 | 0.856 |
| | | Back–3 | 12.0 | 9.1 | 8.4 | 7.3 | 1.158 | 1.126 | 0.808 |
| | | Back–4 | 12.6 | 10.0 | 10.2 | 7.8 | 1.302 | 1.277 | 0.872 |
| L100–5 | 12.7 | Front–1 | 11.9 | 10.4 | 9.9 | 7.8 | 1.264 | 1.256 | 0.872 |
| | | Front–2 | 12.3 | 9.2 | 10.2 | 7.4 | 1.385 | 1.342 | 0.820 |
| | | Back–3 | 14.1 | 10.4 | 10.5 | 8.4 | 1.255 | 1.212 | 0.932 |
| | | Back–4 | 12.9 | 9.9 | 10.7 | 7.9 | 1.362 | 1.328 | 0.875 |
| L100–6 | 12.7 | Front–1 | 11.1 | 10.8 | 10.2 | 7.7 | 1.318 | 1.318 | 0.862 |
| | | Front–2 | 11.2 | 10.8 | 10.2 | 7.8 | 1.312 | 1.312 | 0.866 |
| | | Back–3 | 11.2 | 10.5 | 10.6 | 7.7 | 1.384 | 1.382 | 0.853 |
| | | Back–4 | 12.3 | 9.9 | 9.9 | 7.7 | 1.284 | 1.262 | 0.859 |
| L150–1 † | 12.7 | Front–1 | 12.5 | 11.2 | 9.2 | 8.3 | 1.103 | 1.099 | 0.929 |
| | | Front–2 | 12.4 | 12.3 | 9.6 | 8.7 | 1.100 | 1.100 | 0.972 |
| | | Back–3 | 14.2 | 11.6 | 9.5 | 9.0 | 1.058 | 1.042 | 1.000 |
| | | Back–4 | 13.2 | 12.3 | 9.9 | 9.0 | 1.104 | 1.102 | 0.999 |
| L150–2 † | 12.7 | Front–1 | 13.3 | 11.4 | 9.3 | 8.6 | 1.075 | 1.066 | 0.963 |
| | | Front–2 | 12.9 | 11.8 | 9.4 | 8.7 | 1.081 | 1.078 | 0.969 |
| | | Back–3 | 12.9 | 11.2 | 9.3 | 8.4 | 1.101 | 1.093 | 0.941 |
| | | Back–4 | 13.2 | 11.0 | 9.5 | 8.5 | 1.122 | 1.109 | 0.943 |
| L150–3 † | 12.7 | Front–1 | 12.3 | 10.6 | 9.0 | 8.1 | 1.117 | 1.108 | 0.897 |
| | | Front–2 | 12.2 | 10.2 | 8.9 | 7.8 | 1.141 | 1.127 | 0.869 |
| | | Back–3 | 12.8 | 10.7 | 9.4 | 8.2 | 1.148 | 1.135 | 0.912 |
| | | Back–4 | 12.6 | 11.1 | 9.4 | 8.3 | 1.127 | 1.120 | 0.929 |

**Table E12.5 (cont.)**

| Specimen | Nominal Leg Size (mm) | Weld | MPL (mm) | LPL (mm) | 45° Meas. (mm) | MTD (mm) | Ratio $\alpha_1$ | Ratio $\alpha_2$ | Ratio $\rho_G$ |
|---|---|---|---|---|---|---|---|---|---|
| L150–4 | 12.7 | Front–1 | 13.3 | 11.1 | 9.4 | 8.5 | 1.103 | 1.090 | 0.949 |
| | | Front–2 | 13.7 | 10.2 | 10.0 | 8.2 | 1.222 | 1.184 | 0.911 |
| | | Back–3 | 13.1 | 10.8 | 9.4 | 8.3 | 1.128 | 1.113 | 0.928 |
| | | Back–4 | 13.3 | 10.4 | 9.0 | 8.2 | 1.099 | 1.074 | 0.912 |
| L150–5 | 12.7 | Front–1 | 13.0 | 10.5 | 9.2 | 8.2 | 1.126 | 1.107 | 0.910 |
| | | Front–2 | 12.7 | 10.7 | 9.2 | 8.2 | 1.124 | 1.112 | 0.911 |
| | | Back–3 | 11.9 | 10.4 | 8.6 | 7.8 | 1.098 | 1.091 | 0.872 |
| | | Back–4 | 12.1 | 10.5 | 8.6 | 7.9 | 1.084 | 1.076 | 0.883 |
| L150–6 | 12.7 | Front–1 | 12.0 | 9.6 | 8.2 | 7.5 | 1.094 | 1.074 | 0.835 |
| | | Front–2 | 12.0 | 11.2 | 9.1 | 8.2 | 1.111 | 1.110 | 0.912 |
| | | Back–3 | 12.9 | 10.7 | 10.1 | 8.2 | 1.226 | 1.211 | 0.917 |
| | | Back–4 | 12.6 | 11.3 | 9.3 | 8.4 | 1.105 | 1.101 | 0.937 |
| TNY–1 | 12.7 | Front | 13.4 | 12.2 | 10.7 | 9.0 | 1.190 | 1.186 | 1.002 |
| | | Back | 13.9 | 12.3 | 10.7 | 9.2 | 1.160 | 1.154 | 1.027 |
| TNY–2 | 12.7 | Front | 13.9 | 12.0 | 11.4 | 9.1 | 1.254 | 1.245 | 1.012 |
| | | Back | 14.0 | 12.1 | 10.7 | 9.1 | 1.169 | 1.159 | 1.019 |
| TNY–3 | 12.7 | Front | 14.5 | 12.0 | 10.9 | 9.3 | 1.177 | 1.163 | 1.031 |
| | | Back | 13.6 | 12.5 | 10.7 | 9.2 | 1.162 | 1.159 | 1.026 |
| TYa–1 † | 12.7 | Front | 14.2 | 11.5 | 10.5 | 8.9 | 1.177 | 1.158 | 0.993 |
| | | Back | 13.6 | 11.7 | 11.6 | 8.9 | 1.305 | 1.294 | 0.990 |
| TYa–2 † | 12.7 | Front | 13.9 | 12.3 | 11.4 | 9.2 | 1.238 | 1.231 | 1.025 |
| | | Back | 14.1 | 11.0 | 10.9 | 8.7 | 1.255 | 1.226 | 0.968 |
| TYa–3 † | 12.7 | Front | 13.3 | 10.9 | 10.3 | 8.5 | 1.218 | 1.201 | 0.942 |
| | | Back | 13.2 | 11.8 | 11.3 | 8.8 | 1.288 | 1.282 | 0.977 |
| All Specimens | | | Mean of Ratios | | | | 1.106 | 1.090 | 0.981 |
| | | | Coefficient of Variation, $V$ | | | | 0.085 | 0.088 | 0.082 |

† Test results are reported in Appendix G of this report.

**Table E12.6** – All-Weld-Metal Coupon Tests from Callele *et al.* (2005)

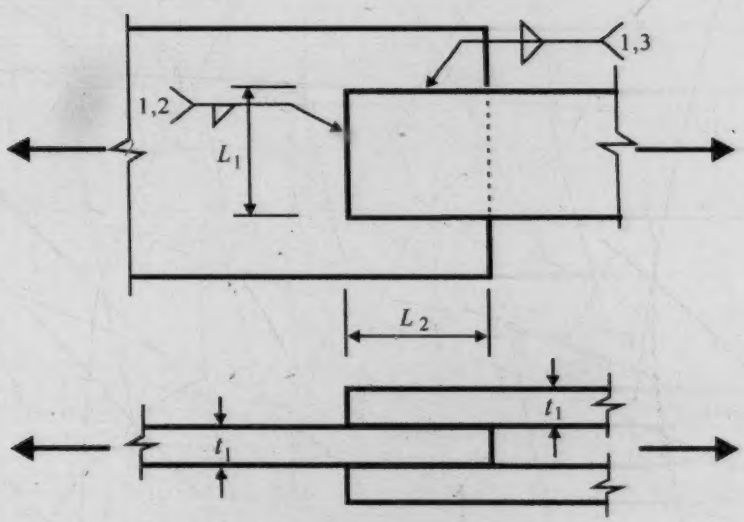
| Electrode | $\sigma_u$ (MPa) | $X_u$ (MPa) | Ratio $\rho_{M1}$ | Mean $\rho_{M1}$ | $V_{M1}$ |
|---|---|---|---|---|---|
| E70T–7 | 571 | 480 | 1.190 | 1.225 | 0.045 |
| | 576 | 480 | 1.200 | | |
| | 578 | 480 | 1.204 | | |
| | 568 | 480 | 1.183 | | |
| | 566 | 480 | 1.179 | | |
| | 574 | 480 | 1.196 | | |
| | 609 | 480 | 1.269 | | |
| | 600 | 480 | 1.250 | | |
| | 584 | 480 | 1.217 | | |
| | 652 | 480 | 1.358 | | |
| E70T–4 | 513 | 480 | 1.069 | 1.179 | 0.079 |
| | 513 | 480 | 1.069 | | |
| | 557 | 480 | 1.160 | | |
| | 557 | 480 | 1.160 | | |
| | 562 | 480 | 1.171 | | |
| | 563 | 480 | 1.173 | | |
| | 630 | 480 | 1.313 | | |
| | 631 | 480 | 1.315 | | |
| E70T7–K2 | 592 | 480 | 1.233 | 1.232 | 0.001 |
| | 591 | 480 | 1.231 | | |
| E71T8–K6 | 495 | 480 | 1.031 | 1.021 | 0.010 |
| | 484 | 480 | 1.008 | | |
| | 488 | 480 | 1.017 | | |
| | 485 | 480 | 1.010 | | |
| | 494 | 480 | 1.029 | | |
| | 495 | 480 | 1.031 | | |
| | 491 | 480 | 1.023 | | |
| E7014 | 517 | 480 | 1.077 | 1.105 | 0.021 |
| | 523 | 480 | 1.090 | | |
| | 543 | 480 | 1.131 | | |
| | 529 | 480 | 1.102 | | |
| | 541 | 480 | 1.127 | | |
| All Electrodes | | | | 1.151 | 0.084 |

**Table E12.7** – Longitudinal Weld Tests from Deng *et al.* (2003) and Callele *et al.* (2005)

| Specimen | Electrode | Model | Equation 4.6a | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Phase | $\tau_u$ (MPa) | $\sigma_u$ (MPa) | $0.67\sigma_u$ (MPa) | Ratio | Mean $\rho_{M2}$ | $V_{M2}$ |
| L1–1 | E70T–4 | 2 | 505 | 631 | 423 | 1.195 | 1.174 | 0.025 |
| L1–2 | | | 482 | | | 1.140 | | |
| L1–3 | | | 502 | | | 1.187 | | |
| L3–1 | E71T8–K6 | 2 | 512 | 493 | 330 | 1.550 | 1.514 | 0.040 |
| L3–2 | | | 477 | | | 1.444 | | |
| L3–3 | | | 511 | | | 1.547 | | |
| L2–1 | E70T–7 | 2 | 536 | 605 | 405 | 1.322 | 1.226 | 0.092 |
| L2–2 | | | 551 | | | 1.359 | | |
| L2–3 | | | 548 | | | 1.352 | | |
| L100–1 | | 3 | 434 | 569 | 381 | 1.138 | | |
| L100–2 | | | 429 | | | 1.125 | | |
| L100–3 | | | 475 | | | 1.246 | | |
| L100–4 | | | 422 | | | 1.107 | | |
| L100–5 | | | 397 | | | 1.041 | | |
| L100–6 | | | 444 | | | 1.165 | | |
| L150–4 | | | 453 | | | 1.188 | | |
| L150–5 | | | 500 | | | 1.312 | | |
| L150–6 | | | 519 | | | 1.361 | | |
| All Specimens | | | | | | | 1.266 | 0.118 |

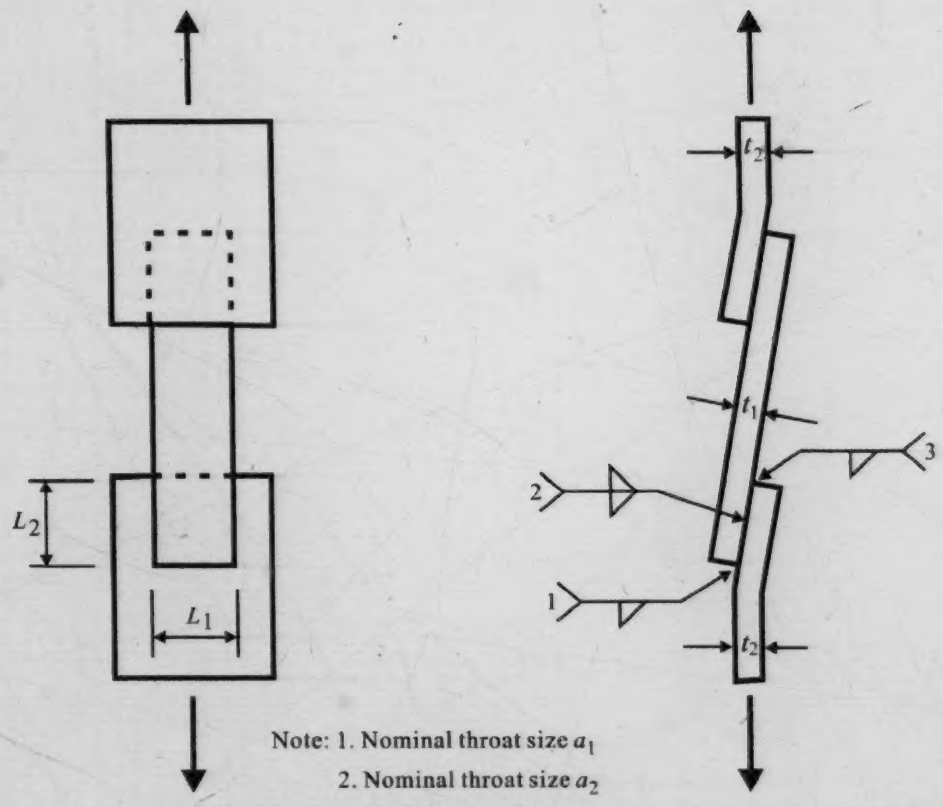
**Table E12.8** – Analysis of Test Results from Callele *et al.* (2005) – Combined Transverse and Longitudinal Welds

| Specimen | Model | Specimen with Transverse and Longitudinal Weld | | | | | |
|---|---|---|---|---|---|---|---|
| | | Equation 4.9 | | Equation 4.10 | | Equation 4.10a and b | |
| | $P_u$ (kN) | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ | Predicted Capacity (kN) | Ratio $\rho_P$ |
| TL50–1 | 1484 | 1792 | 0.828 | 1923 | 0.772 | 1792 | 0.828 |
| TL50–2 | 1664 | 1778 | 0.936 | 1911 | 0.871 | 1778 | 0.936 |
| TL50–3 | 1573 | 1785 | 0.881 | 1911 | 0.823 | 1785 | 0.881 |
| TL50–4 | 1700 | 1811 | 0.939 | 1945 | 0.874 | 1811 | 0.939 |
| TL50a–1 | 1299 | 1573 | 0.826 | 1687 | 0.770 | 1573 | 0.826 |
| TL50a–2 | 1186 | 1618 | 0.733 | 1738 | 0.683 | 1618 | 0.733 |
| TL50a–3 | 1213 | 1592 | 0.762 | 1707 | 0.710 | 1592 | 0.762 |
| TL50a–4 | 1472 | 1738 | 0.847 | 1866 | 0.789 | 1738 | 0.847 |
| TL100–1 | 2359 | 2824 | 0.835 | 3116 | 0.757 | 2824 | 0.835 |
| TL100–2 | 2218 | 2627 | 0.844 | 2903 | 0.764 | 2627 | 0.844 |
| TL100–3 | 1976 | 2662 | 0.742 | 2933 | 0.674 | 2662 | 0.742 |
| TL100SP–1 | 2032 | 2222 | 0.915 | 2462 | 0.825 | 2222 | 0.915 |
| TL100SP–2 | 1866 | 2190 | 0.852 | 2425 | 0.769 | 2190 | 0.852 |
| TL100SP–3 | 1813 | 2193 | 0.827 | 2424 | 0.748 | 2193 | 0.827 |
| TL100D–1 | 2077 | 2235 | 0.929 | 2469 | 0.841 | 2235 | 0.929 |
| TL100D–2 | 2040 | 2149 | 0.949 | 2370 | 0.861 | 2149 | 0.949 |
| TL100D–3 | 2341 | 2709 | 0.864 | 3001 | 0.780 | 2709 | 0.864 |
| TL50D–1 | 1486 | 1769 | 0.840 | 1902 | 0.781 | 1769 | 0.840 |
| TL50D–2 | 1455 | 1836 | 0.793 | 1973 | 0.738 | 1836 | 0.793 |
| TL50D–3 | 1412 | 1745 | 0.809 | 1882 | 0.750 | 1745 | 0.809 |
| All specimen | Mean $\rho_P$ | | 0.848 | | 0.779 | | 0.848 |
| | $V_P$ | | 0.075 | | 0.073 | | 0.075 |




Note 1. Same on both sides of joint
2. Nominal throat size $a_1$
3. Nominal throat size $a_2$

**Figure E1** – General Configuration of Specimens (Ligtenberg, 1968)




Note: 1. Nominal throat size $a_1$
2. Nominal throat size $a_2$
3. Nominal throat size $a_4$

**Figure E2** – Configuration of Type [xx4xx] Specimens

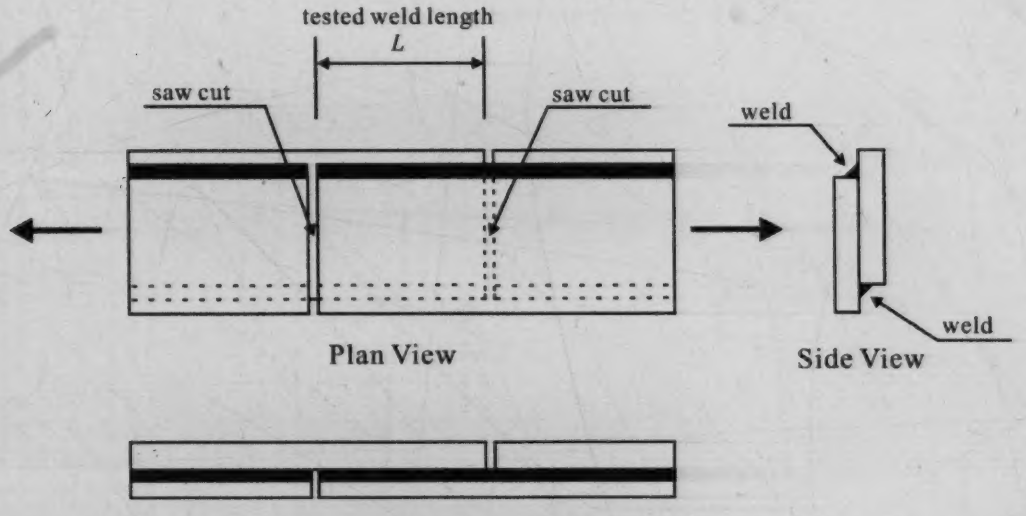



**Figure E3** – Werner Specimen

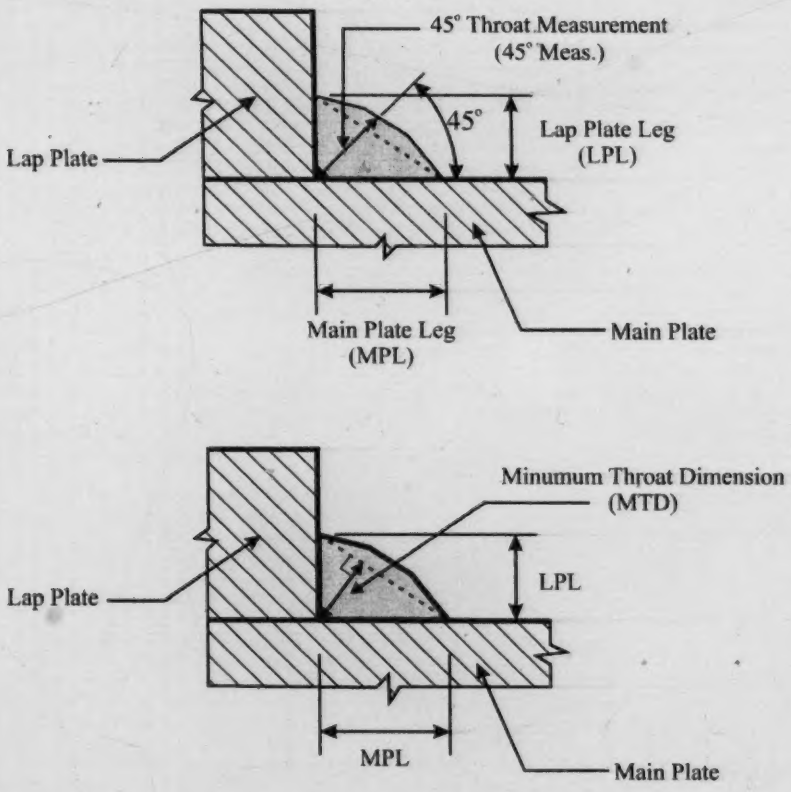



**Figure E4** – Definition of Weld Legs

# APPENDIX F

# NEW SPECIMEN DESIGN DRAWINGS

# APPENDIX F

# NEW SPECIMEN DESIGN DRAWINGS

## F.1 Introduction

This appendix presents the fabrication notes and drawings for specimens that were ordered but not fabricated yet. Aspects of these future tests have been discussed in Chapter 5.

## F.2 General Notes

### FABRICATION GENERAL NOTES

University of Alberta Fillet Weld Project—Phase 5

The attached drawings contain the information required to fabricate the specimens requested. The pertinent information for fabricating each specimen is found on the respective drawing; however the following General Notes apply to all fabrication.

At the top-right corner of every attached drawing there is a label, "PHASE 5". Use these labels to keep track of the number of specimens that are required to be fabricated. In total there are 10 joint-specimens and 3 all-weld-metal specimens that need to be fabricated.

1. Two steels are used in this phase. Some specimens use ASTM Grade 50 Steel, alternative of which is CAN/CSA-G40.21 350W. Some specimens use CAN/CSA-G40.21 300WT or 350WT, whichever is available. However, 350WT is preferred.

2. Do NOT grind the welds. No STOP/START allowed except at plate edges.

3. All plates of a particular thickness shall be of the same heat. There are three different plate thickness that are required for the specimen fabrication, namely, 2", 1-1/2" and 7/8".

4. Provide a copy of the mill certificate for each heat for approval prior to fabrication.

5. Two different AWS electrode classifications are required for fabrication: E70T-7 and E70T7-K2. Respectively, the manufacturer designation of electrodes is described below. Lincoln Electric designation for E70T-7 is Innershield NR311 and Lincoln Electric designation for E70T7-K2 is Innershield NR311Ni.

6. Produce all welds of the identical electrode classification from the same spool.

7. Produce three (3) all-weld-metal specimens shown on the drawing titled "Material Test Specimen".

8. Provide the lot number for each electrode classification used.

9. A Welding Procedure Specification (WPS) shall be submitted for approval prior to fabrication.

10. Record and provide a copy of all welding parameters as measured during welding of the specimens.

11. All specimens shall be marked with their respective specimen designations, see attached drawings. Use surface markings only; no punching or scoring is permitted.

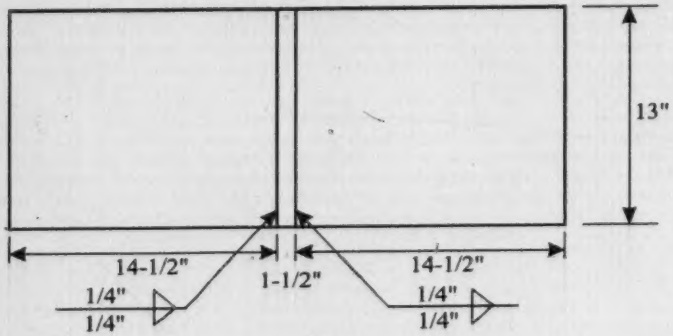
**F.3 Drawings**

Eleven fabrication drawings are presented in the following pages.

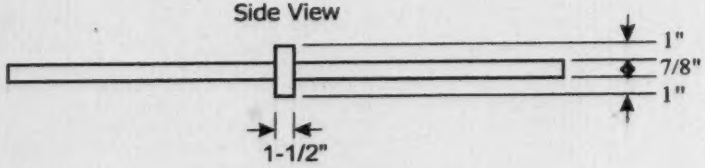
PHASE 5

**Final Assembly**

Top View



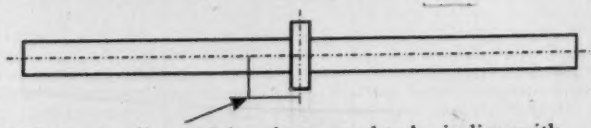

Side View




Weld Leg Size Tolerance: ±1/16"

**Quality Control Criteria**

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

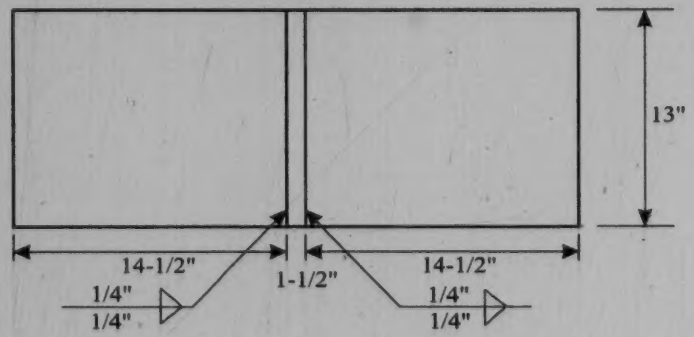
Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T-7 Electrodes i.e. Lincoln Electric designation: Innershield NR311
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in ONE (1) pass

| | | |
|---|---|---|
| Drawn By: Li, C. | Cruciform Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen CYa-1,2,3 | |
| | Scale: NTS | Drawing 1 of 11 |

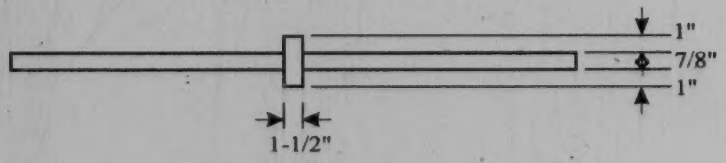
PHASE 5

**Final Assembly**

Top View



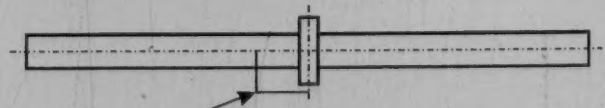

Side View




Weld Leg Size Tolerance: ±1/16"

**Quality Control Criteria**

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



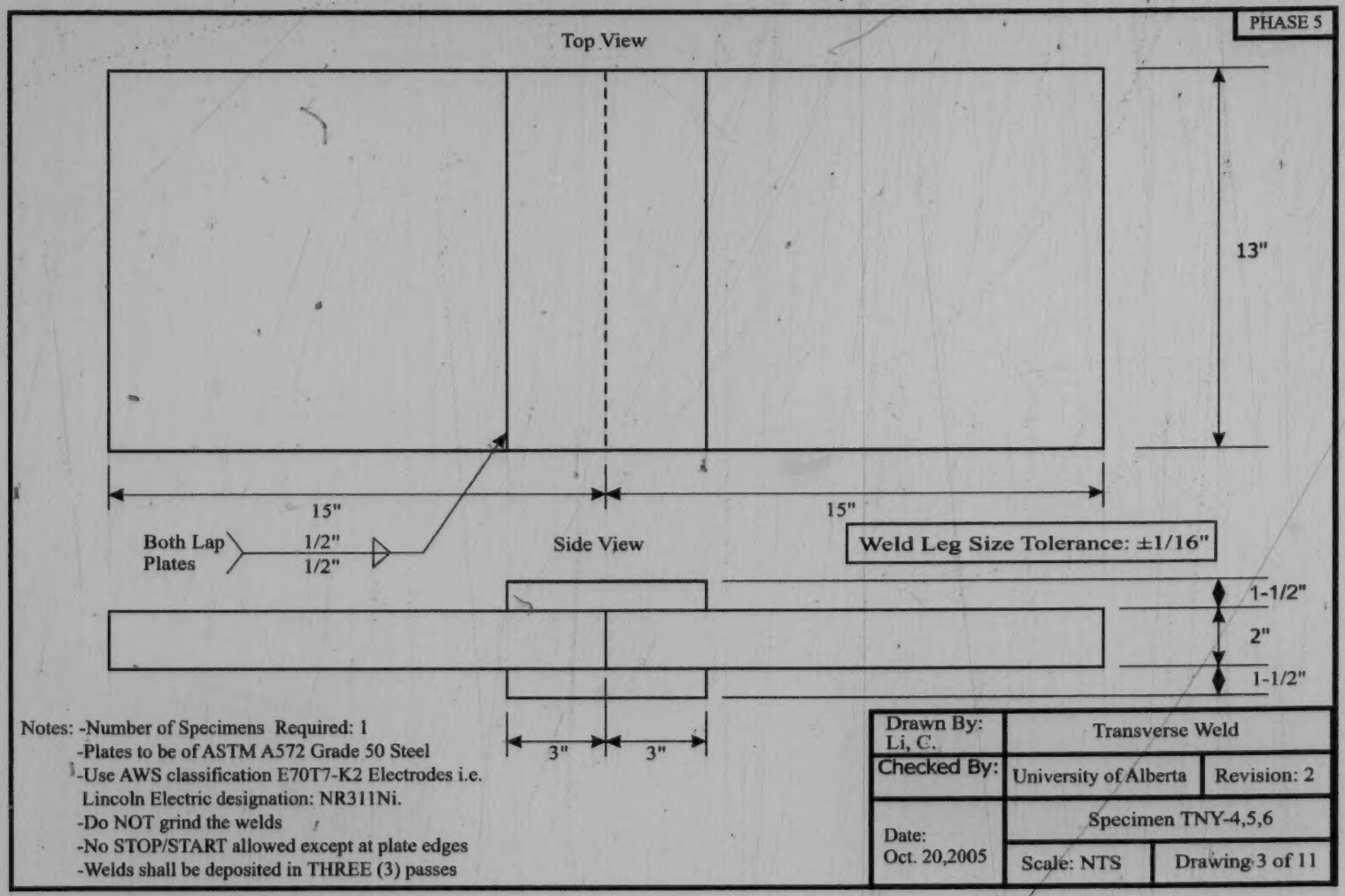
The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in ONE (1) pass

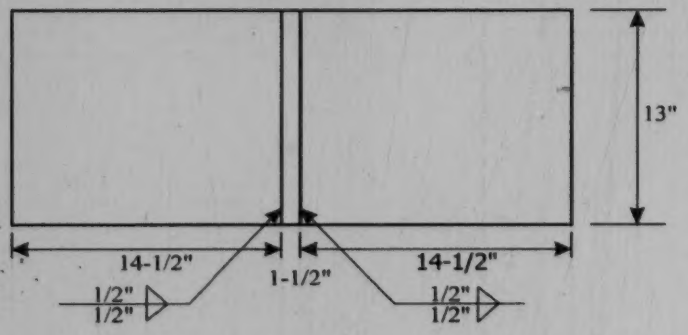
| | | |
|---|---|---|
| Drawn By: Li, C. | Cruciform Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen CYb-1,2,3 | |
| | Scale: NTS | Drawing 2 of 11 |


PHASE 5
Top View
13"
15"
15"
Both Lap Plates
1/2"
1/2"
Side View
Weld Leg Size Tolerance: ±1/16"
1-1/2"
2"
1-1/2"
3"
3"
Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes
Drawn By: Li, C.
Transverse Weld
Checked By:
University of Alberta
Revision: 2
Date: Oct. 20,2005
Specimen TNY-4,5,6
Scale: NTS
Drawing 3 of 11

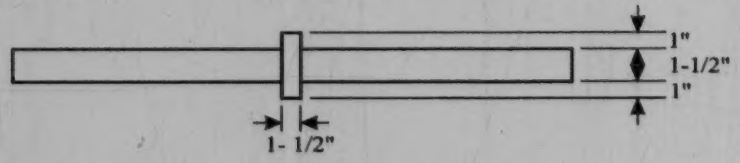
PHASE 5

**Final Assembly**

Top View

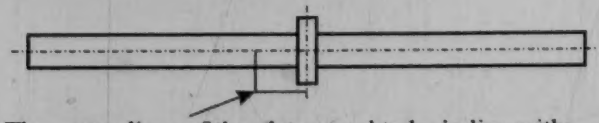



Side View




**Quality Control Criteria**

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure that the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

Weld Leg Size Tolerance: ±1/16"

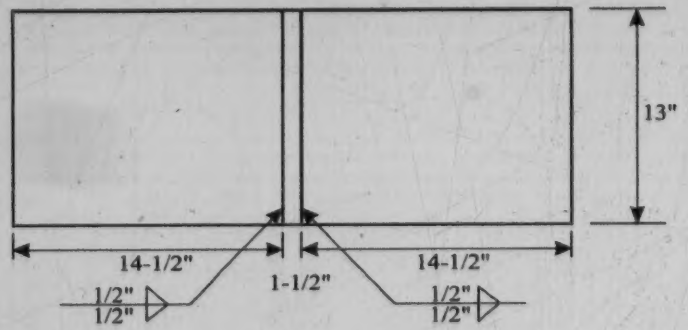
Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T-7 Electrodes i.e. Lincoln Electric designation: Innershield NR311
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes

| | | |
|---|---|---|
| Drawn By: Li, C. | Cruciform Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen CNY-13,14,15 | |
| | Scale: NTS | Drawing 4 of 11 |

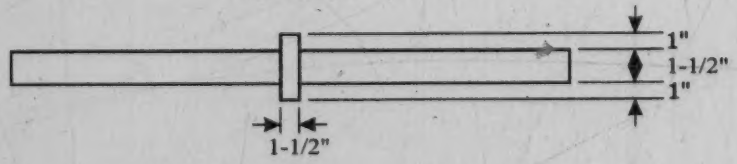
PHASE 5

**Final Assembly**

Top View



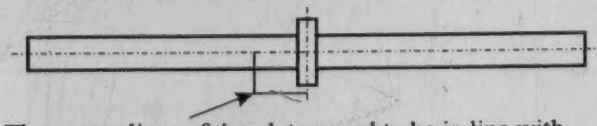

Side View




Weld Leg Size Tolerance: ±1/16"

**Quality Control Criteria**

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure that the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

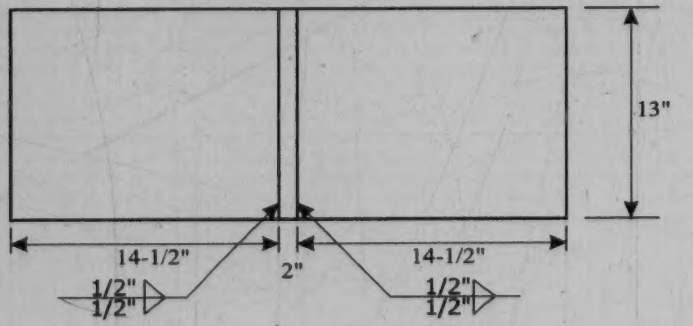
Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes

| | | |
|---|---|---|
| Drawn By: Li, C. | Cruciform Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen CNY-16,17,18 | |
| | Scale: NTS | Drawing 5 of 11 |

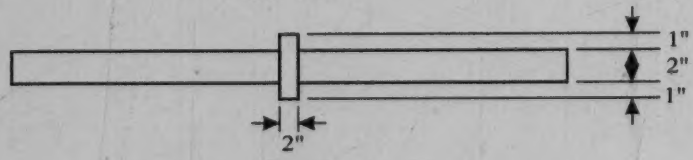
PHASE 5

## Final Assembly

Top View




Side View

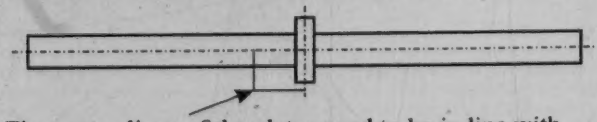



**Weld Leg Size Tolerance: ±1/16"**

Notes: -Number of Specimens Required: 1
-Plates to be of CSA G40.21 Grade 300WT or 350WT Steel
-Use AWS classification E70T7-K2 Electrodes i.e.
Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes

**Quality Control Criteria**

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

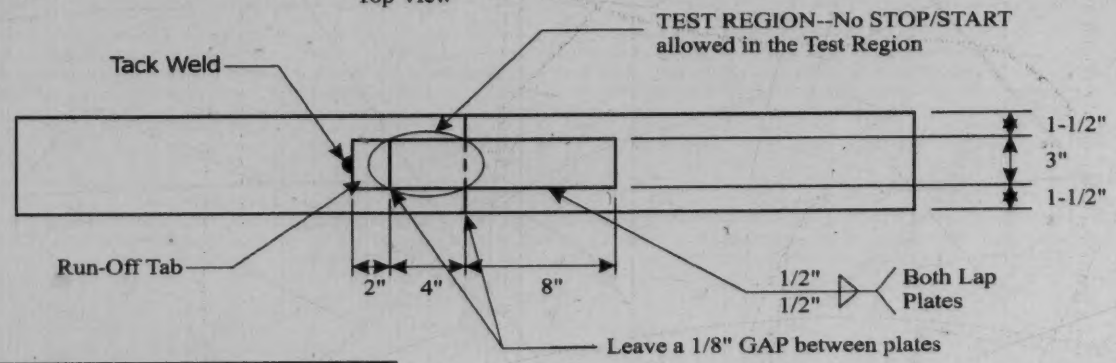
The plates should be clamped down to limit the plate distortion during welding and to ensure that the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

| | | |
|---|---|---|
| Drawn By: Li, C. | Cruciform Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen CNY-19,20,21 | |
| | Scale: NTS | Drawing 6 of 11 |

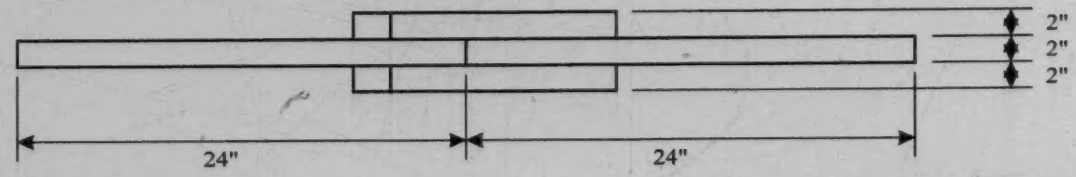
PHASE 5

Top View




Weld Leg Size Tolerance: ±1/16"

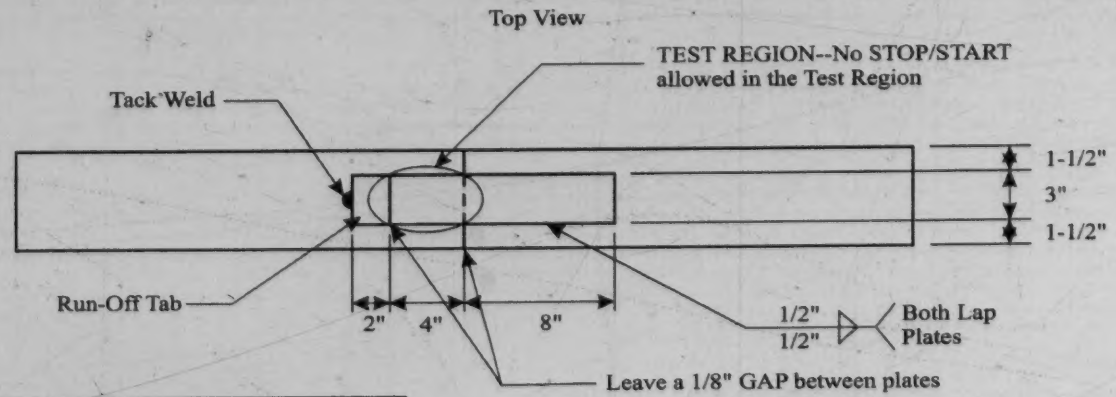
Side View



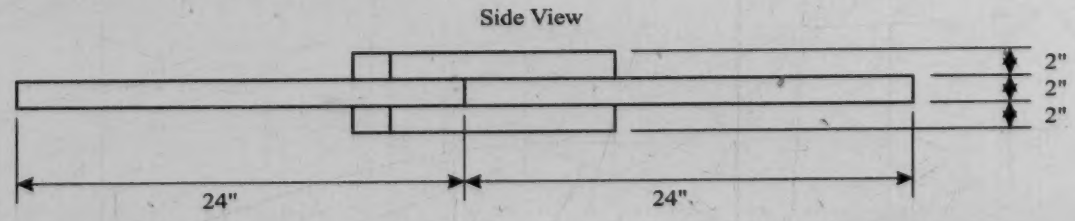

Notes: -Number of Specimens Required: 3
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START in test region
-Welds shall be deposited in THREE (3) passes

| | | |
|---|---|---|
| Drawn By: Li, C. | Longitudinal Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen L100-7, 8, 9 | |
| | Scale: NTS | Drawing 7 of 11 |

PHASE 5



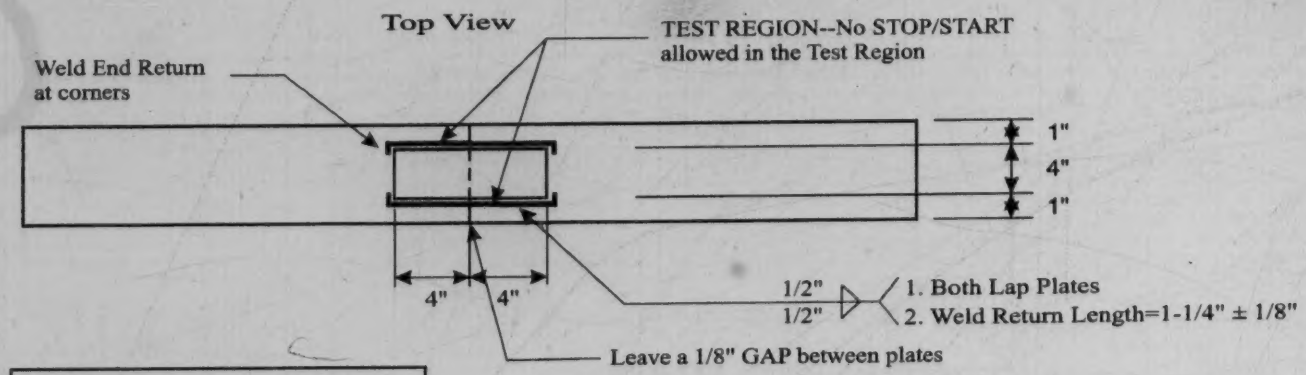

Weld Leg Size Tolerance: ±1/16"



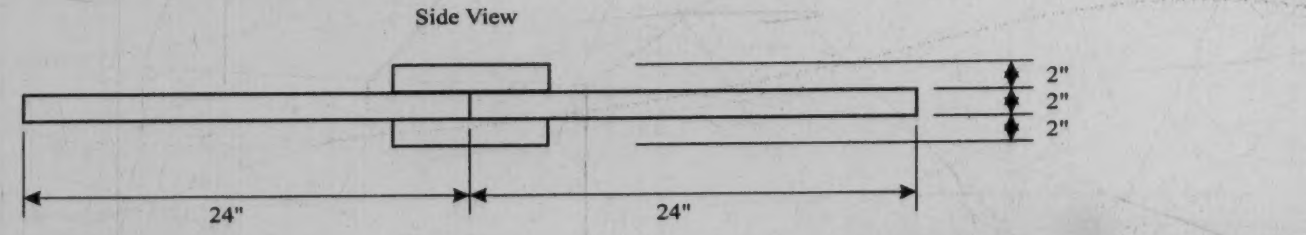

Notes: -Number of Specimens Required: 3
-Plates to be of CSA G40.21 Grade 300WT or 350WT Steel
-Use AWS classification E70T7-K2 Electrodes i.e.
Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed in test region
-Welds shall be deposited in THREE (3) passes

| | | |
|---|---|---|
| Drawn By: Li, C. | Longitudinal Weld | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen L100-10,11,12 | |
| | Scale: NTS | Drawing 8 of 11 |

PHASE 5



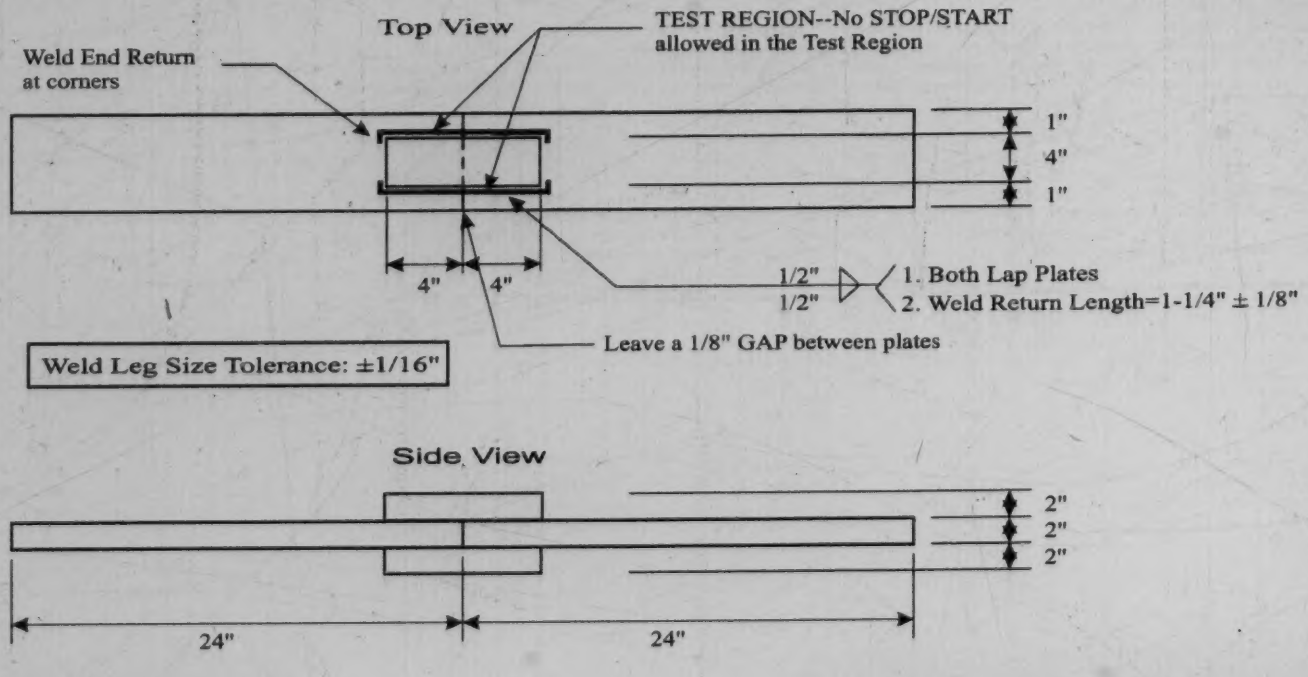

Weld Leg Size Tolerance: ±1/16"




Notes: -Number of Specimens Required: 3
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T-7 Electrodes i.e. Lincoln Electric designation: Innershield NR311
-Do NOT grind the welds
-No STOP/START allowed in test region
-Welds shall be deposited in THREE (3) passes

| | | |
|---|---|---|
| Drawn By: Li, C. | Longitudinal Weld with End Returns | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen L100e-1,2,3 | |
| | Scale: NTS | Drawing 9 of 11 |

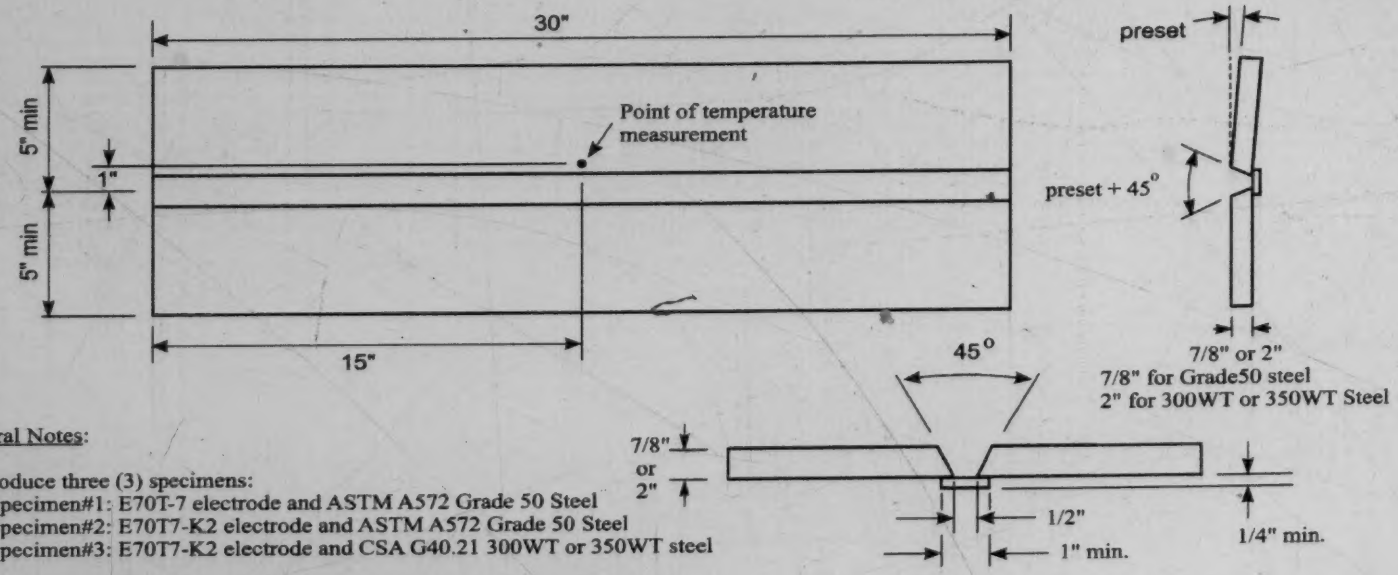
PHASE 5




Notes: -Number of Specimens Required: 3
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes

| | | |
|---|---|---|
| Drawn By: Li, C. | Longitudinal Weld with End Returns | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Specimen L100e-4,5,6 | |
| | Scale: NTS | Drawing 10 of 11 |

PHASE 5




General Notes:

1) Produce three (3) specimens:
   Specimen#1: E70T-7 electrode and ASTM A572 Grade 50 Steel
   Specimen#2: E70T7-K2 electrode and ASTM A572 Grade 50 Steel
   Specimen#3: E70T7-K2 electrode and CSA G40.21 300WT or 350WT steel

2) Welding shall be in the flat position and the assembly shall be restrained, or preset, or a combination of both, during welding to prevent warping in excess of 5 degrees. An assembly that is warped by more than 5 degrees from plane shall be discarded. It shall not be straightened.

3) The test assembly shall be tack welded at room temperature and welding shall begin at that temperature (16 °C minimum). Welding shall continue until the assembly has reached a temperature of 150 ± 14°C, measured by temperature indicating crayons or surface thermometers at the location shown in the figure. This interpass temperature shall be maintained for the remainder of the weld. Should it be necessary to interrupt welding, the assembly shall be allowed to cool in still air at room temperature. The assembly shall be heated to a temperature of 150 ± 14°C before welding is resumed.

| | | |
|---|---|---|
| Drawn By: GYG/RGD | Material Test Specimen | |
| Checked By: | University of Alberta | Revision: 2 |
| Date: Oct. 20,2005 | Phase 5 Weld Metal Coupons | |
| | Scale: NTS | Drawing 11 of 11 |

# APPENDIX G

## RESULTS OF ADDITIONAL SIX SPECIMENS TESTED IN PHASE 4

# APPENDIX G

# RESULTS OF ADDITIONAL SIX SPECIMENS TESTED IN PHASE 4

## G.1 Introduction

This appendix presents six specimens tested in phase 4 but not reported elsewhere in the thesis. They will be incorporated into future work on fillet weld behaviour and are documented here as a record for future use.

Specimens L150-1, 2, 3 each had four 152 mm long longitudinal welds, as shown in Figure G1. The specimens were fabricated using filler metal E70T-7. The specimens were tested at -50 ℃ and the plates remained elastic during testing. The pre-test measurements are presented in Tables G1 through G3. Specimens TYa-1, 2, 3 each had two transverse welds, as shown in Figure G2. The specimens were fabricated using filler metal E70T-7. The specimens were tested at room temperature and the plates yielded during testing. The pre-test measurements are presented in Tables G4 through G6.

The measured capacities are summarized in Table G7 and the measured deformations in Table G8. The response curves are presented in Figures G3 through G8.

The test setup for these specimens was the same as that described in Deng *et al.* (2003). The definitions of the pre-test measurements are also the same as in Deng *et al.* (2003).

**Table G1** – Weld Measurements for Specimen L150–1

| Meas. Number | Front Face | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Weld 1 | | | | Weld 2 | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) |
| 1 | 11.9 | 11.3 | 8.1 | 150.0† | 12.2 | 12.3 | 8.9 | 148.8† |
| 2 | 11.9 | 10.7 | 9.0 | 150.0† | 11.2 | 13.0 | 9.7 | 148.7† |
| 3 | 12.9 | 10.3 | 9.4 | 158.2‡ | 11.5 | 12.3 | 9.4 | 159.2‡ |
| 4 | 13.8 | 11.4 | 9.8 | | 13.5 | 11.8 | 9.7 | |
| 5 | 12.6 | 11.3 | 8.9 | | 12.9 | 12.3 | 9.8 | |
| 6 | 12.7 | 12.0 | 9.2 | | 12.4 | 12.3 | 9.7 | |
| 7 | 12.9 | 12.1 | 9.5 | | 13.0 | 12.0 | 9.7 | |
| 8 | 12.2 | 10.7 | 9.2 | | 12.3 | 12.5 | 10.0 | |
| 9 | 11.7 | 11.0 | 8.9 | | 12.3 | 12.2 | 9.7 | |
| 10 | 12.1 | 10.1 | 9.8 | | 12.7 | 11.9 | 9.4 | |
| Mean | 12.5 | 11.1 | 9.2 | | 12.4 | 12.3 | 9.6 | |
| Meas. Number | Back Face | | | | | | | |
| | Weld 3 | | | | Weld 4 | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) |
| 1 | 13.2 | 11.3 | 8.9 | 150.8† | 13.1 | 11.2 | 9.5 | 149.9† |
| 2 | 13.4 | 11.5 | 9.4 | 150.5† | 13.9 | 11.7 | 10.0 | 149.5† |
| 3 | 13.5 | 12.2 | 10.0 | 158.8‡ | 14.4 | 12.3 | 9.8 | 155.6‡ |
| 4 | 14.7 | 11.6 | 9.8 | | 12.1 | 12.0 | 9.7 | |
| 5 | 14.9 | 12.1 | 9.8 | | 13.1 | 12.8 | 10.2 | |
| 6 | 14.1 | 12.2 | 9.7 | | 14.3 | 12.5 | 10.6 | |
| 7 | 13.8 | 10.7 | 9.0 | | 12.9 | 12.5 | 10.0 | |
| 8 | 14.2 | 10.9 | 9.4 | | 13.8 | 13.2 | 10.2 | |
| 9 | 15.3 | 11.2 | 9.4 | | 12.1 | 13.1 | 9.7 | |
| 10 | 15.5 | 11.3 | 9.4 | | 11.9 | 11.5 | 9.5 | |
| Mean | 14.2 | 11.5 | 9.5 | | 13.2 | 12.3 | 9.9 | |

**Table G2** – Weld Measurements for Specimen L150–2

| Meas. Number | Front Face | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Weld 1 | | | | Weld 2 | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) |
| 1 | 13.1 | 10.5 | 8.9 | 151.0† | 13.1 | 11.6 | 9.0 | 148.3† |
| 2 | 12.2 | 11.1 | 9.2 | 150.6† | 12.5 | 11.8 | 9.5 | 148.3† |
| 3 | 13.1 | 11.9 | 9.2 | 158.6‡ | 13.4 | 11.4 | 9.4 | 160.2‡ |
| 4 | 13.7 | 11.2 | 9.7 | | 13.5 | 11.3 | 9.2 | |
| 5 | 13.4 | 11.6 | 9.5 | | 13.6 | 11.8 | 9.5 | |
| 6 | 14.1 | 11.7 | 10.0 | | 13.3 | 12.3 | 9.7 | |
| 7 | 14.0 | 11.4 | 9.8 | | 12.3 | 11.9 | 9.5 | |
| 8 | 14.2 | 11.8 | 9.4 | | 12.0 | 12.6 | 9.0 | |
| 9 | 12.5 | 11.3 | 8.9 | | 12.3 | 11.7 | 9.5 | |
| 10 | 12.6 | 11.5 | 8.6 | | 12.4 | 11.7 | 9.4 | |
| Mean | 13.3 | 11.4 | 9.3 | | 12.9 | 11.8 | 9.4 | |
| Meas. Number | Back Face | | | | | | | |
| | Weld 3 | | | | Weld 4 | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) |
| 1 | 13.2 | 10.3 | 9.4 | 151.6† | 12.5 | 10.1 | 8.4 | 152.0† |
| 2 | 13.0 | 10.0 | 8.4 | 151.7† | 13.8 | 10.7 | 9.4 | 152.2† |
| 3 | 13.3 | 10.9 | 9.4 | 160.9‡ | 13.1 | 11.0 | 9.8 | 160.5‡ |
| 4 | 12.4 | 11.7 | 9.8 | | 13.8 | 11.3 | 10.2 | |
| 5 | 12.9 | 12.0 | 9.8 | | 13.3 | 11.4 | 10.0 | |
| 6 | 13.2 | 12.1 | 9.5 | | 13.4 | 11.1 | 10.5 | |
| 7 | 13.7 | 11.7 | 9.2 | | 13.3 | 11.6 | 9.7 | |
| 8 | 12.5 | 11.7 | 9.5 | | 12.2 | 11.2 | 8.6 | |
| 9 | 12.1 | 11.3 | 8.9 | | 13.4 | 10.9 | 9.2 | |
| 10 | 12.4 | 10.5 | 9.2 | | 13.3 | 11.2 | 9.5 | |
| Mean | 12.9 | 11.2 | 9.3 | | 13.2 | 11.0 | 9.5 | |

**Table G3** – Weld Measurements for Specimen L150–3

| Meas. Number | Front Face | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Weld 1 | | | | Weld 2 | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) |
| 1 | 12.2 | 11.1 | 8.7 | 151.8† | 11.6 | 10.7 | 8.3 | 150.5† |
| 2 | 11.6 | 9.5 | 8.4 | 151.6† | 11.9 | 10.6 | 8.3 | 150.8† |
| 3 | 12.6 | 10.1 | 9.2 | 159.4‡ | 12.3 | 10.6 | 8.9 | 157.8‡ |
| 4 | 13.0 | 11.4 | 9.5 | | 12.2 | 9.8 | 9.0 | |
| 5 | 13.1 | 11.4 | 9.8 | | 12.4 | 9.6 | 8.9 | |
| 6 | 12.7 | 10.8 | 9.2 | | 13.4 | 10.7 | 9.4 | |
| 7 | 13.3 | 10.1 | 9.0 | | 12.7 | 11.1 | 9.7 | |
| 8 | 12.6 | 10.0 | 8.7 | | 12.0 | 10.1 | 9.5 | |
| 9 | 11.5 | 11.1 | 9.0 | | 11.8 | 9.1 | 9.0 | |
| 10 | 11.0 | 10.9 | 8.6 | | 11.8 | 9.3 | 8.3 | |
| Mean | 12.3 | 10.6 | 9.0 | | 12.2 | 10.2 | 8.9 | |

| Meas. Number | Back Face | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Weld 3 | | | | Weld 4 | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length† / Gauge Length‡ (mm) |
| 1 | 13.0 | 10.0 | 8.9 | 147.5† | 12.1 | 11.0 | 9.0 | 148.1† |
| 2 | 12.5 | 10.6 | 9.0 | 147.2† | 12.6 | 11.3 | 9.5 | 148.3† |
| 3 | 11.8 | 10.4 | 9.2 | 157.5‡ | 12.7 | 11.5 | 9.4 | 157.95‡ |
| 4 | 12.9 | 11.2 | 9.7 | | 12.2 | 10.8 | 9.2 | |
| 5 | 14.0 | 11.0 | 10.0 | | 12.9 | 11.3 | 9.5 | |
| 6 | 13.8 | 11.2 | 9.8 | | 13.3 | 11.6 | 9.7 | |
| 7 | 12.4 | 11.3 | 9.4 | | 13.3 | 11.0 | 9.5 | |
| 8 | 12.8 | 10.8 | 9.5 | | 13.1 | 11.1 | 9.0 | |
| 9 | 12.3 | 9.8 | 9.5 | | 12.3 | 10.8 | 9.5 | |
| 10 | 12.1 | 10.5 | 8.9 | | 11.9 | 10.6 | 9.4 | |
| Mean | 12.8 | 10.7 | 9.4 | | 12.6 | 11.1 | 9.4 | |

**Table G4** – Weld Measurements for Specimen TYa–1

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 13.6 | 11.0 | 9.5 | 76.2 | 15.0 | 11.5 | 12.4 | 76.2 |
| 2 | 13.3 | 11.4 | 9.7 | 76.2 | 13.7 | 11.6 | 11.4 | 76.3 |
| 3 | 13.9 | 11.6 | 10.8 | 76.2 | 14.6 | 11.7 | 11.4 | 76.2 |
| 4 | 14.2 | 12.6 | 10.8 | — | 13.6 | 12.0 | 11.3 | — |
| 5 | 15.1 | 12.0 | 10.6 | — | 13.9 | 11.6 | 11.4 | — |
| 6 | 14.6 | 11.0 | 11.0 | — | 12.9 | 11.5 | 11.1 | — |
| 7 | 13.7 | 11.3 | 11.0 | — | 12.7 | 11.7 | 11.4 | — |
| 8 | 14.8 | 11.0 | 10.8 | — | 12.8 | 12.3 | 12.2 | — |
| Mean | 14.2 | 11.5 | 10.5 | 76.2 | 13.6 | 11.7 | 11.6 | 76.2 |
| Gauge Length (mm) | LVDT1 = 19.0 | | | | LVDT2 = 16.5 | | | |
| | LVDT3 = 22.5 | | | | LVDT4 = 21.0 | | | |

**Table G5** – Weld Measurements for Specimen TYa–2

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 13.7 | 12.2 | 11.4 | 76.3 | 14.3 | 11.1 | 11.0 | 76.3 |
| 2 | 13.8 | 11.9 | 11.6 | 76.3 | 14.4 | 10.6 | 11.0 | 76.3 |
| 3 | 13.1 | 12.1 | 11.3 | 76.3 | 14.8 | 10.7 | 11.0 | 76.3 |
| 4 | 14.4 | 12.0 | 11.4 | — | 14.7 | 11.3 | 11.0 | — |
| 5 | 15.2 | 12.4 | 11.4 | — | 14.2 | 11.4 | 10.8 | — |
| 6 | 14.0 | 12.5 | 11.4 | — | 13.8 | 11.0 | 10.8 | — |
| 7 | 14.4 | 12.3 | 11.3 | — | 13.4 | 11.0 | 10.8 | — |
| 8 | 13.0 | 12.7 | 11.4 | — | 13.2 | 11.2 | 10.8 | — |
| Mean | 13.9 | 12.3 | 11.4 | 76.3 | 14.1 | 11.0 | 10.9 | 76.3 |
| Gauge Length (mm) | LVDT1 = 17.6 | | | | LVDT2 = 15.0 | | | |
| | LVDT3 = 16.7 | | | | LVDT4 = 15.7 | | | |

**Table G6** – Weld Measurements for Specimen TYa–3

| Meas. Number | Pre-Test Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Front Face | | | | Back Face | | | |
| | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length (mm) | MPL (mm) | LPL (mm) | 45° Meas. (mm) | Weld Length (mm) |
| 1 | 13.4 | 11.0 | 10.2 | 76.2 | 13.2 | 11.9 | 11.4 | 76.2 |
| 2 | 13.7 | 11.2 | 10.2 | 76.2 | 12.6 | 11.9 | 11.3 | 76.2 |
| 3 | 12.9 | 11.7 | 10.2 | 76.2 | 13.3 | 12.3 | 11.4 | 76.2 |
| 4 | 12.5 | 11.6 | 10.5 | — | 13.3 | 11.3 | 11.3 | — |
| 5 | 13.0 | 10.8 | 10.3 | — | 13.1 | 11.4 | 11.1 | — |
| 6 | 14.1 | 10.4 | 10.2 | — | 12.9 | 11.7 | 11.0 | — |
| 7 | 13.6 | 10.4 | 10.3 | — | 13.8 | 12.0 | 11.6 | — |
| 8 | 13.5 | 10.4 | 10.5 | — | 13.1 | 11.6 | 11.6 | — |
| Mean | 13.3 | 10.9 | 10.3 | 76.2 | 13.2 | 11.8 | 11.3 | 76.2 |
| Gauge Length (mm) | LVDT1 = 17.8 | | | | LVDT2 = 13.9 | | | |
| | LVDT3 = 19.7 | | | | LVDT4 = 13.9 | | | |

**Table G7** – Summary of Specimens Capacity

| Specimen | Electrode | $P_u$ Ultimate Load (kN) | Static Drop | | | $P_{ST} = P_u - \Delta P$ (kN) | Total Area $A_{throat}$ ($mm^2$) | $P_{ST} / A_{throat}$ (MPa)) | Average $P_{ST} / A_{throat}$ | Weld Failed |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | upper | lower | ΔP(kN) | | | | | |
| L150–1 | E70T–7 | 2269 | 2208 | 2184 | 24 | 2245 | 5243 | 428 | 450 | Back |
| L150–2 | | 2389 | 2292 | 2258 | 34 | 2355 | 5161 | 456 | | Plate |
| L150–2 | | 2299 | 2281 | 2243 | 38 | 2261 | 4840 | 467 | | Plate |
| TYa–1 | E70T–7 | 1063 | 999 | 967 | 32 | 1031 | 1356 | 761 | 754 | Back |
| TYa–2 | | 1081 | 1072 | 1039 | 33 | 1048 | 1325 | 791 | | Back |
| TYa–3 | | 990 | 988 | 959 | 29 | 961 | 1338 | 710 | | Back |

**Table G8** – Summary of Specimens Ductility

| Specimen | | LVDT 1 | LVDT 2 | LVDT 3 | LVDT 4 | LVDT 6 | LVDT 7 |
|---|---|---|---|---|---|---|---|
| | | (mm) | (mm) | (mm) | (mm) | (mm) | (mm) |
| L150–1 | Ultimate | 0.925 | 1.050 | 1.802 | 1.898 | 1.327 | 2.040 |
| L150–2 | Ultimate | 1.346 | 1.505 | 1.471 | 1.647 | 1.724 | 1.807 |
| L150-3 | Ultimate | 1.346 | 1.505 | 1.471 | 1.647 | 1.724 | 1.807 |
| TYa–1 | Ultimate | 1.470 | 1.493 | 1.734 | 1.771 | — | — |
| | Fracture | 1.523 | 1.571 | 2.480 | 2.440 | — | — |
| TYa–2 | Ultimate | 1.784 | 1.888 | 1.472 | 1.980 | — | — |
| | Fracture | 2.462 | 2.637 | 1.607 | 2.077 | — | — |
| TYa–3 | Ultimate | 1.067 | 1.113 | 1.461 | 1.819 | — | — |
| | Fracture | 1.118 | 1.150 | 1.870 | 2.291 | — | — |

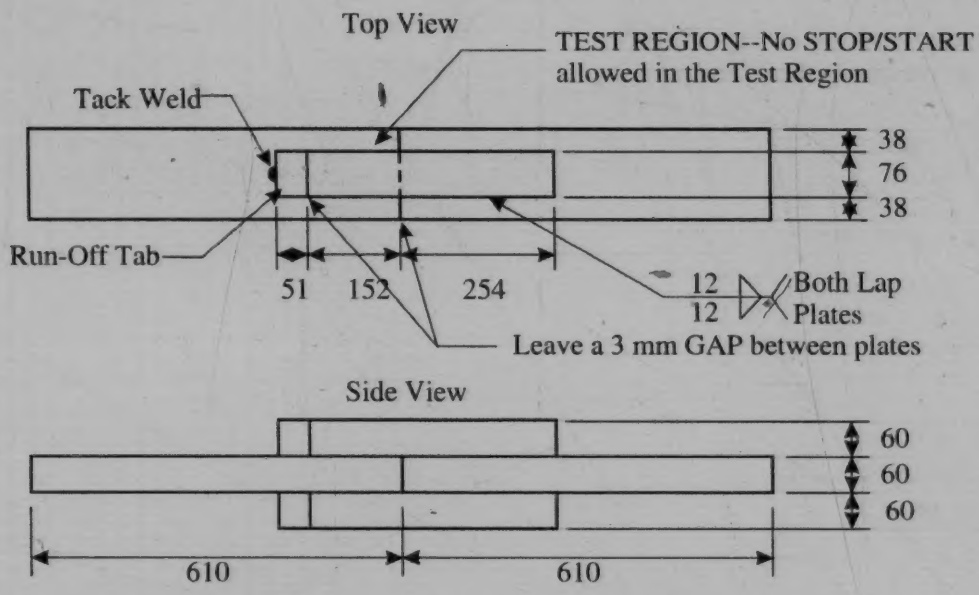



**Figure G1** – Specimen L150–1, 2, 3 with Dimensions

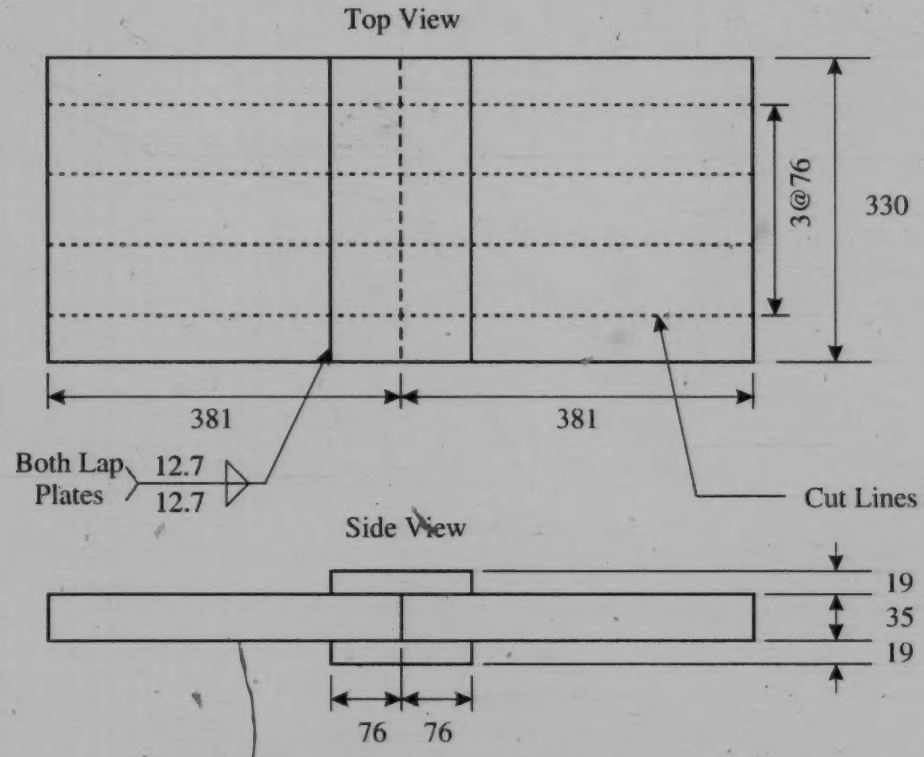



**Figure G2** – Specimen TYa–1, 2, 3 with Dimensions

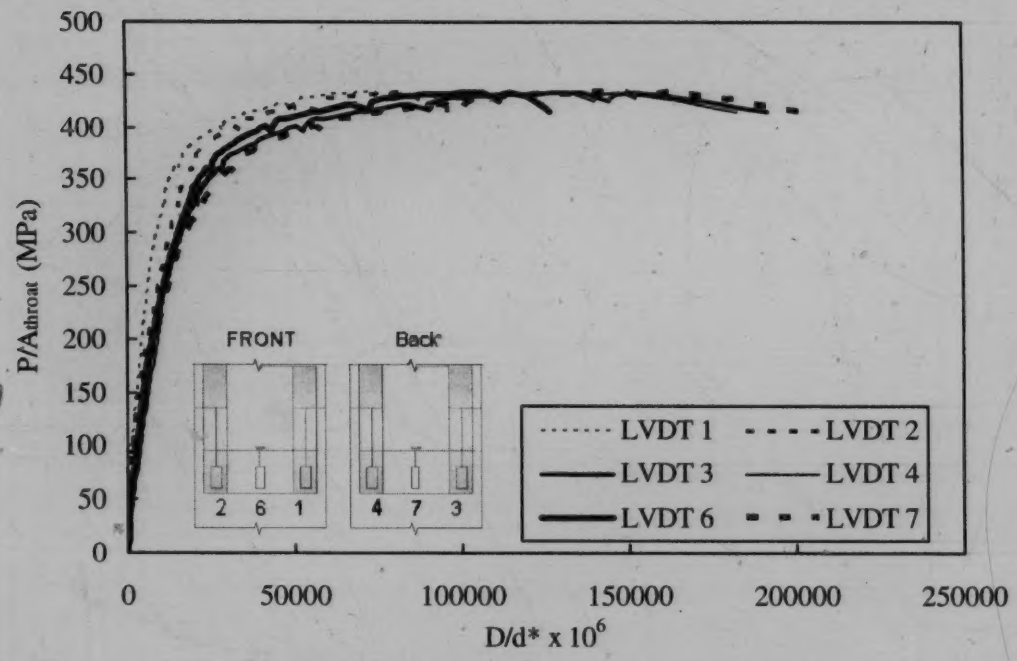



**Figure G3** – Response Curve for Specimen L150–1

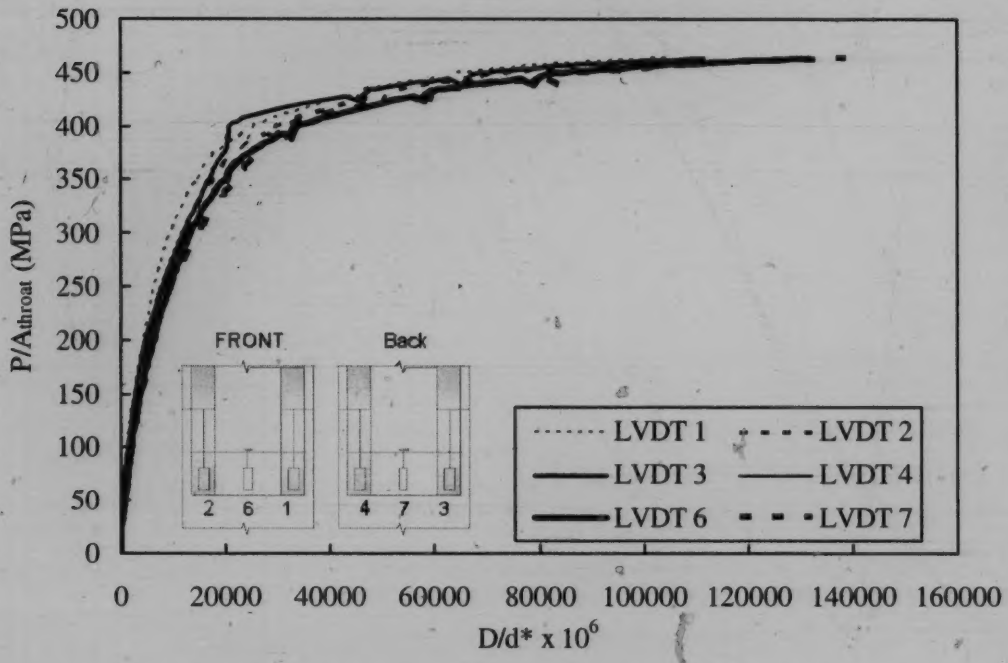



**Figure G4** – Response Curve for Specimen L150–2

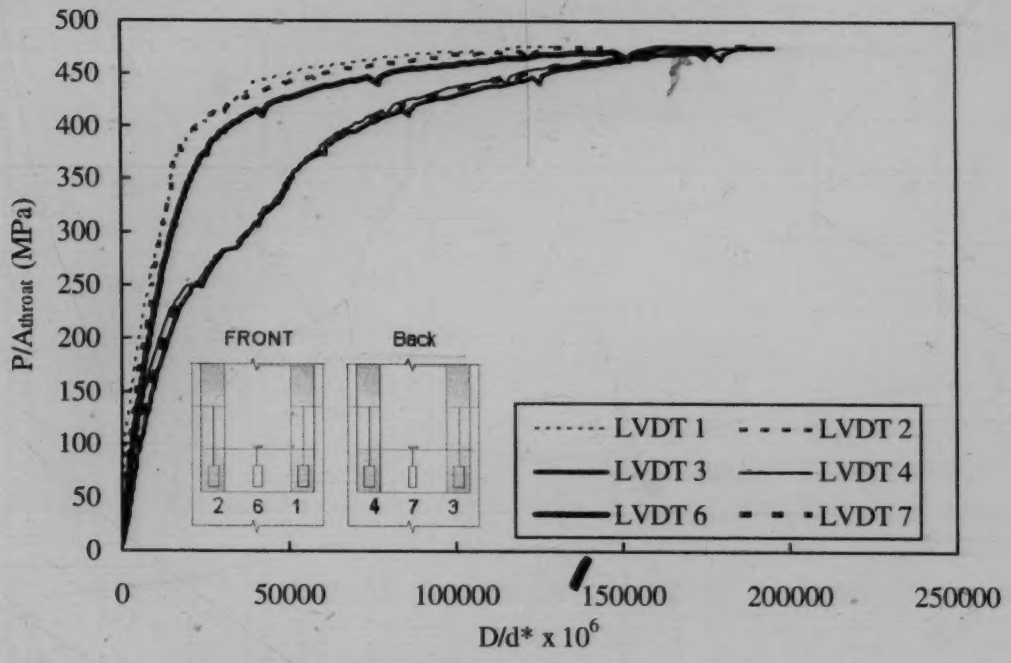



**Figure G5** – Response Curve for Specimen L150–3

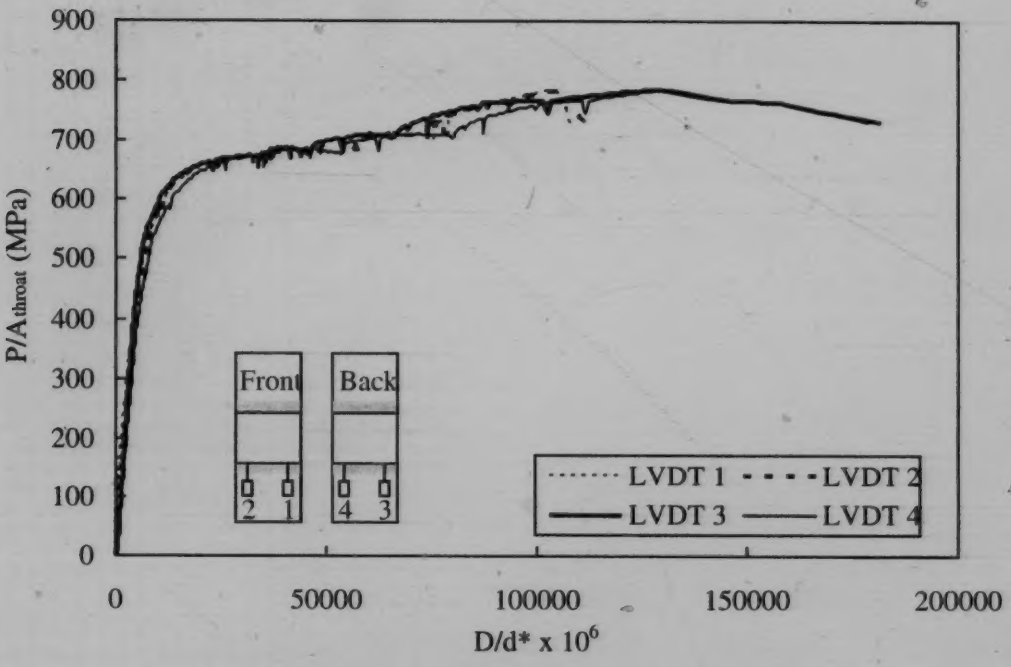



**Figure G6** – Response Curve for Specimen TYa–1

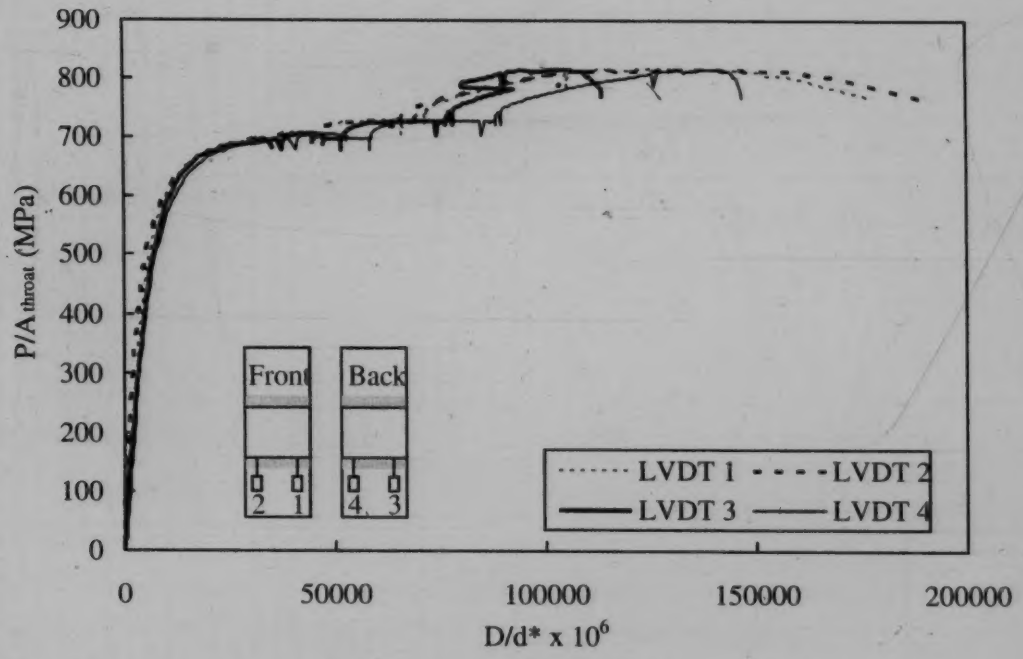



**Figure G7** – Response Curve for Specimen TYa–2

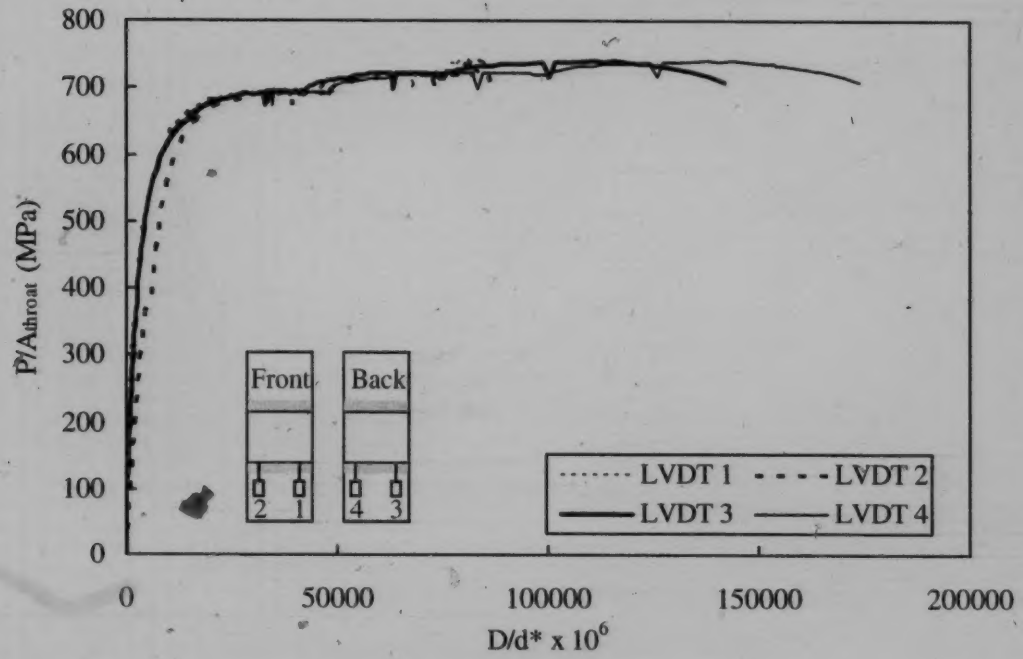



**Figure G8** – Response Curve for Specimen TYa–3